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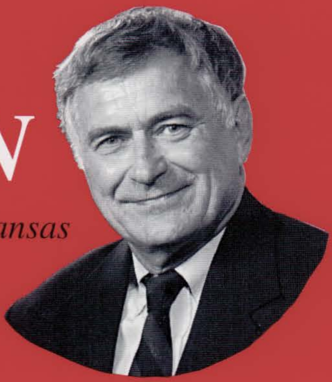
Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers

DON GREEN

of the University of Kansas



AWARD LECTURE

SPECIAL SECTION

THE FUTURE OF ENGINEERING EDUCATION

...and chemical engineering at

Oklahoma State University

Chemical Engineering Education
Volume 34 Number 1 Winter 2000

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ChE department

Chemical Engineering at . . .

OKLAHOMA STATE UNIVERSITY

◄ *Theta Pond, on the path between classes and housing.*

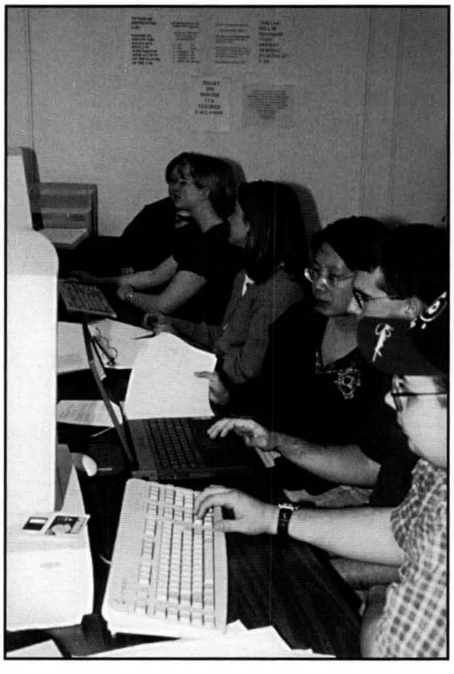
▼ *Design groups. Left to right: Seniors Jill Petersen, Melissa Hayes, Sally Gerhold, Ting Chung, Mike Hill, and T.J. Crowell collaborating on process design homework.*

R. RUSSELL RHINEHART
Oklahoma State University • Stillwater, OK 74078-5021

Quality in education has been a defining value in the School of Chemical Engineering at Oklahoma State University (OSU) since its inception in 1917. Developing students who will ultimately benefit their community has a different tone from simply challenging students on their ability to memorize facts and calculation procedures. While competency in the fundamentals of chemical engineering science and methodology remains important, developing people who are creative and effective within a team environment, who manage their own growth, and who make good things happen is the goal at OSU.

The school also has a mission to develop new knowledge and tools for engineering. This vision guides the graduate research program where students and faculty work closely together to both create and discover.

Students' first-place awards in national team design championships, their outstanding student-chapter awards, national scholarships, and performance on the Fundamentals of Engineering Exam are all testaments to the fact that human resource development is working at OSU.



STRENGTH IN THE TEAM

"I continue to be impressed with the collegiality of the faculty," says Dr. Karen High, whose specialty is optimization. This is a theme expressed by many of the faculty. In Jan Wagner's words, "What attracted me to OSU was the professionalism of the faculty throughout the college. They pull together." Jan's interest is safety and management of change. Kinetics expert Gary Foutch recalls the "candor, fun, mentoring, and support of the senior faculty. Decisions are made for the best interest of the School, not for individuals."

Mutual support among the faculty expresses the value that all benefit when any one individual has success. And whether cooperation is on research or on continuous improvement, the synergism and balance from partnerships makes the final result better. Collaboration is a value: it is a way of interacting with other people, and it carries over from the faculty to the undergraduate and graduate programs as well. Respect between faculty and students, and respect between students is important to the maximization of student learning and research performance.

Even while struggling to make sense of lab data, senior Melissa Hays recalls that "OSU followed through with a personal interest in me when I was seeking a college, and throughout my time here, I have always felt that the chemical engineering faculty care for and respect the students." Jake Dearman, also a senior, adds, "The main reason that I came here was because the campus was friendly and caring. Faculty want to see the students grow personally and professionally, and that atmosphere is conducive to learning." To integrate students into the program, all engineering students enroll in ENGR1111, where they are led by a faculty mentor, learn about engineering and about the values and attitudes promoted at OSU, and are encouraged to participate in school activities.

Chemical engineering is a difficult curriculum with a significant challenge—it must prepare students to use a complicated technology for the good of society. At OSU, students work in teams to help each other solve complex problems and to encourage each other through the personal ups and downs of the program. The faculty's open-door policy affirms the importance of the student's learning activity. Even the arrangement of faculty offices—suites off of one reception area—engenders a common team mission: "All for one, one for all."

The activities of the Student Chapter of the American Institute of Chemical Engineers and of Omega Chi Epsilon (the ChE honorary) also enhance student/faculty interaction. Events include formal speaker meetings, drop-in pizza dinner, golf tournaments, picnics, and service activities that integrate students and faculty. In fact, the AIChE Student Chapter has earned a National Outstanding Chapter Award for three of the past four years.

But it's not just a party. While it is fun, it is also hard work.

QUALITY

OSU was named "Best College Buy" by Institutional Research and Evaluation, Inc., in their *Student Guide to America's 100 Best College Buys: 1999.*

"As a former OSU student, I was familiar with the quality of the program and its potential for growth. I knew that I'd have many talented colleagues with whom I could associate in my research area of thermodynamics. I also felt a sense of loyalty and commitment to OSU," reflects Rob Robinson, Regents Professor, Amoco Chair, and former School Head. Long before the new EC 2000 criteria, the School established a tradition of continuous assessment, including feedback from an Industrial Advisory Committee, and experienced frequent revision of the priorities that guided its goals and objectives.

Chronology of Events

School of Chemical Engineering
Oklahoma State University

1890 Oklahoma Agricultural and Mechanical College (A&M) established

1907 Oklahoma Territory granted Statehood

1909 First chemical engineering course within Department of Chemistry

1917 Chemical Engineering BS Degree plan granted

1921 First BS ChE graduates

1938 AIChE Student Chapter granted

1947 Chemical Engineering moves from Chemistry to the Division of Engineering

1948 Policy: Each engineering student will take a course from each engineering program

1951 ChE Ph.D. program approved

1953 First ChE Ph.D. granted

1957 A&M becomes Oklahoma State University

1964 Omega Chi Epsilon (Mu Chapter) ChE Scholastic Honorary chartered

1964 Industrial Advisory Committee established

1966 Phillips Lecture Series in ChE Education started

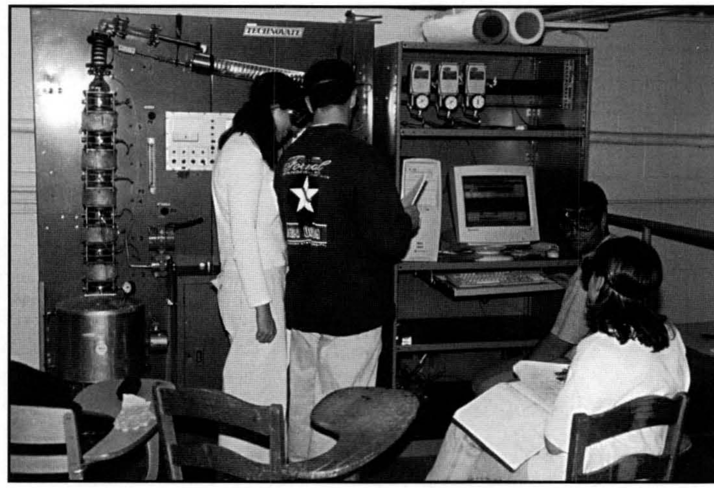
1984 Pre-medical BS option started

1993 Environmental Engineering BS option started

While competency in the fundamentals of chemical engineering science and methodology remains important, developing people who are creative and effective within a team environment, who manage their own growth, and who make good things happen is the goal at OSU.

The department has been very fortunate to have the Phillips Petroleum Company as a co-sponsor of the Phillips Lecture Series in Chemical Engineering Education, an annual lecture at Oklahoma State University now in its 33rd year. Speakers have established themselves as leaders in education, and reprints of their lectures are distributed nationally. "My first awareness of Oklahoma State University," recounts Russ Rhinehart, School Head and Bartlett Chair, "came as a result of the lecture pamphlets. I was preparing for a new career in academe, and the stimulating lectures generated respect for the School."

Of course, the program is ABET accredited.



Unit Operations: Tamika Killian, Chad Smith, Mike Dickenson, and Sally Gerhold as operators on a computer-controlled distillation.

"Unit Operations Lab is fun!"—the often-heard sentiment describes the students' team apprenticeship on distillation, reaction, heat exchange, refrigeration, absorption, and fluid-flow processes. In the classroom, the concepts are isolated and idealized so students can learn the fundamentals of chemical process behavior, but since the behavior is neither ideal nor isolated in real process equipment, students are also taught how to deal with such complexity before they are released to practice their profession. With professors taking the role of "coaches" and students the role of team "players," the Unit Operations Laboratory is a place where active mentoring shows the students how to apply the fundamentals to the real world. Features include "360" evaluations, student ownership of experimental design, and conversion of lab findings into business decisions.

Process Design and Economics is also a practice-oriented course. Two full-time professors manage the course and coach the student teams. The Celanese Chemical Company provides an annual design challenge, and their engineers evaluate the students' oral and written presentations as well as the technical work.

BALANCE

"Balancing fundamentals with practice, as well as research with education were important attributes to me when I was looking for a school," says School Head Russ Rhinehart. Emeritus Professor and heat-exchanger expert Ken Bell notes, "The program has always emphasized the practicality of technology in both teaching and research." The career experience of chemical engineering faculty at OSU averages five years of full-time practice. The result is that they understand how engineers need to work and they integrate that knowledge into their classes.

This balance can be credited to former Head, and Emeritus Professor Robert N. Maddox, who initiated the Phillips educational lectures as well as the Industrial Advisory Committee (IAC) in the '60s. The role of the IAC is to "provide advice and council to the faculty of the School of Chemical Engineering. All areas of operation will be open to criticism and suggestion." Those values remain important today.

This experience also shapes the graduate research program (where about half of the funding is industrial), which includes three industrially sponsored consortia. Gary Foutch, Regents Professor and Kerr-McGee Chair, leads a group concerned with ultrapure water. "The Ultrapure Water Group is a consortium that has existed for eight years now. The eight companies in the group represent nuclear power, microelectronics, domestic water, and the Navy nuclear program. The primary research focus is to develop accurate models that will predict the performance of contaminant removal from water where the concentrations of interest are at the parts-per-trillion level. Students in the group frequently have the opportunity to work in the industry as co-ops."

Centers are created to enhance industrial and academic research-and-development collaborations. The newest is the Measurement and Control Engineering Center (MCEC), a joint collaboration with the University of Tennessee, Knoxville, the US National Science Foundation, and twenty companies to explore and guide the practicable application of advanced techniques for process automation. OSU participants include four professors and five graduate students. Led at OSU by Dr. Karen High, it includes sponsorship of work by Russ Rhinehart in nonlinear control and management automation, Rob Whiteley in fault detection, Gary Yen (Electrical and Computer Engineering) in computer perception, and Karen's work in optimization in process design and control.

Jan Wagner and Marty High lead the downhole corrosion consortium. One product from this consortium is a Windows software package that can predict the location and rate of corrosion in both sweet and sour natural gas wells. The project not only aims to solve the practical problem of corrosion in the petroleum industry, but also involves the fundamental study of fluid mechanics, thermodynamics, corrosion kinetics, and mass transfer.

Certainly, one of the leading indicators of either industrial or academic success is the student's ability to understand and apply fundamentals. Evidence of this competence is demonstrated by student performance on the Fundamentals of Engineering (FE) Exam, administered nationally by the NCEES. It is a comprehensive test of competence in engineering material, and passing it is the first step toward becoming registered as a professional engineer. For the past five years, OSU chemical engineering students have consistently shown a 92% pass rate on the exam. Nationally, the pass rate for chemical engineering graduates is 83%. OSU's

TABLE 1
Faculty • Oklahoma State University School of Chemical Engineering

Gary L. Foutch, Ph.D., P.E., Kerr-McGee Chair and Regents Professor
Ph.D., Chemical Engineering, University of Missouri-Rolla, 1980
Ultrapure Water Processing, Reaction Kinetics and Reactor Design
National Fulbright Scholarship Selection Committee

Khaled A.M. Gasem, Ph.D., R.N. Maddox Professor
Ph.D., Chemical Engineering, Oklahoma State University, 1986
Thermodynamic and Transport Studies, Equilibrium Calculation Algorithms, Process Design and Simulation
Integrated Petroleum Environmental Consortium co-founder and liaison to the US Congress

James E. Halligan, Ph.D., Professor, System CEO, OSU President
Ph.D., Chemical Engineering, Pennsylvania State University
People, Development

Karen A. High, Ph.D., Associate Professor
Ph.D., Chemical Engineering, Pennsylvania State University, 1991
Optimization, Kinetic and Reactor Modeling, Environmental-Based Process Design and Optimization, Parallel Optimization
Director AIChE Division 10 (Computing and Systems Technology)

Martin S. High, Ph.D., P.E., Associate Professor
Ph.D., Chemical Engineering, Pennsylvania State University, 1990
Equations of State for Polymer Solutions, Diffusion of Polymer Molecules, Downhole Corrosion Rates

Arland H. Johannes, Ph.D., P.E., Professor
Ph.D., Chemical Engineering, University of Kentucky, 1977
Interfacial Mass Transfer, Mathematical Modeling, Heterogeneous Catalysis and Energy Conversion Systems, Hazardous Waste Disposal, Fluidized Bed Reactors

Randy S. Lewis, Ph.D., Associate Professor
Ph.D., Chemical Engineering, Massachusetts Inst. of Technology, 1995
Biomass Conversion to Liquid Fuels, Drug Delivery, Artificial Organs, Biomaterials
Past National Student Chapters Committee Chair of the AIChE, Member of the National AIChE Career and Education Operating Council

R. Russell Rhinehart, Ph.D., Edward E. Bartlett Chair and School Head
Ph.D., Chemical Engineering, North Carolina State University, 1985
Nonlinear and Statistical Methods in Process Optimization and Control
Editor-in-Chief of ISA Transactions, General Chair of the 2002 American Control Conference

Robert L. Robinson, Jr., Ph.D., P.E., Amoco Chair and Regents Professor
Ph.D., Chemical Engineering, Oklahoma State University, 1964
Equilibrium Behavior, Design of Solvents for Extractive Distillation, Equation-of-State Representations, Adsorption
Director of the National Technological University ChE program, Fellow AIChE

Alan Tree, Ph.D., Associate Professor, Interim Associate Dean for Research
Ph.D., Chemical Engineering, University of Illinois, 1990
Polymer Science and Engineering, Flow-Induced Crystallization, Melt Rheology

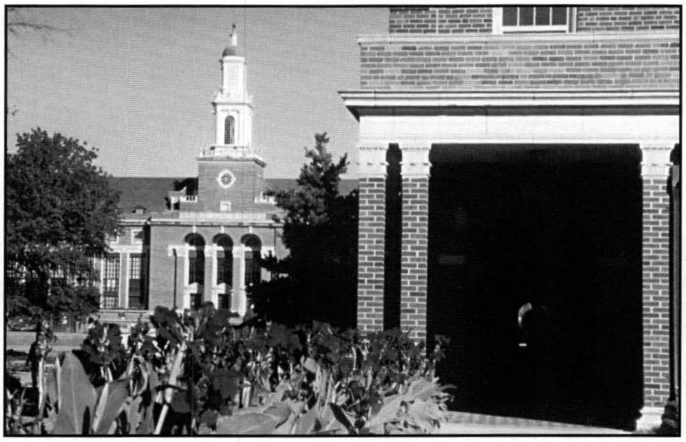
Jan Wagner, Ph.D., P.E., Professor
Ph.D., Chemical Engineering, University of Kansas, 1976
Process Safety, Process Design, Phase Equilibria and Equations of State
Member AIChE/CCPS SACHE Committee and editor of SACHE News

James Robert Whiteley, Ph.D., P.E., Associate Professor
Ph.D., Chemical Engineering, Ohio State University, 1991
Advanced Process Control, Artificial Intelligence Applications in the Process Industries

Kenneth J. Bell, Ph.D., P.E. Regents Professor Emeritus
Ph.D., Chemical Engineering (Physics minor), Univ. of Delaware, 1955
Fluid Dynamics, Heat Transfer, Heat Exchangers
AIChE Fellow, 1978 AIChE Donald Q. Kern Award, 1999 AIChE HT&EC Division Award

Robert N. Maddox, Ph.D., Sc.D., P.E. Leonard F. Sheerar Distinguished Professor Emeritus, Head Emeritus
Ph.D., Chemical Engineering, Oklahoma State University, 1955
Gas Processing
Sc.D. honors causa University of Arkansas 1991; 1985 GPA Hanlon Award; 1994 AIChE Founders Award

Marvin M. Johnson, Ph.D., Adjunct Professor
Ph.D., Chemical Engineering, University of Utah, 1956
Kinetics and Catalysts
AIChE Fellow; 1985 National Medal of Technology Recipient; 1994 National Academy of Engineering inductee



◀ ***Edmond Low Library, center of the OSU campus.***

Students, faculty, and alumni enjoy a pre-game picnic. University President Jim Halligan talks with Professors Karen and Marty High. ▼

sustained 92% pass rate is one clear indication of excellence in both students and faculty.

Fundamentals are important, but engineers have to integrate fundamentals, apply them, and devise a solution that meets all of the criteria for goodness. Perhaps one indication of excellence here is OSU's record of accomplishment in the National AIChE Student Design Contests. In the five-year history of the team contest, Oklahoma State student teams have won first place twice. Since 1953, they have also received many honorable mentions and first-place awards for the individual design contest.

As stated earlier, collegiality was an initial attraction for Dr. Jan Wagner, but he goes on to say, "The most enjoyable thing now is the work ethic and values of the students. We have high expectations, and the students meet them." Professor "AJ" Johannes seconds this; "Warm weather, low taxes, and friendly, honest people were the initial attraction to Oklahoma State. But, it is the hard-working honest students that make every day a joy."

GRADUATE RESEARCH

The School emphasizes basic research, and here, too, there is a practice-relevant component. "I was attracted to OSU by the expertise in processing, process development, and the practice orientation in phase behavior," says Khaled Gasem, Maddox Professor. One of OSU's premier graduate research programs has been that of Professors Khaled Gasem and Rob Robinson in their experimental findings and equation-of-state development for the thermodynamic behavior of multicomponent phase equilibrium. Their U.S. Department of Energy-funded research on carbon dioxide sequestering in coal beds has the dual purposes of reducing CO_2 in the air while enhancing natural gas production. They are also developing techniques for using molecular simulation software to "design" specialty solvents for extractive distillation, and have demonstrated industrial success. Their work has a strong experimental component and employs about a dozen graduate and undergraduate students.

Randy Lewis, Associate Professor, has collaborative biotechnology research projects with several departments, each with experimental credibility. He is exploring novel routes to use bacteria to generate liquid fuels from renewable resources, developing mathematical models for analysis of drug delivery, analyzing immune response molecules and their role in the dysfunction of an artificial pancreas, and developing biomaterials that control local nitric oxide levels and prevent platelet adhesion on implanted materials. Randy's primary funding has come from the National Institutes of Health and the Department of Energy. He is also the advisor to the award-winning Student Chapter, one of the prime reasons for its success.

Can you make a bridge smart enough to take heat from the ground to prevent freezing when the surface is wet? "Yes," according to Associate Professor Rob Whiteley, who is collaborating with civil, mechanical, and technology professors on a DOT-sponsored project. Rob and his students are responsible for the artificial intelligence that reacts to weather forecasts and underground conditions and manages the ground-source heat pumps. Rob is a regular winner of college and university teaching awards.

Martin High ("Dr. Marty") and Alan Tree have a shared interest in the fundamentals of polymer kinetics and thermodynamics. "The long, chain-like nature of polymer molecules allows them to crystallize under certain flow conditions, resulting in structures with superior mechanical properties. Part of our NSF funding has been used to support experimental and theoretical efforts that extend classical crystallization theory to account for flow-induced behavior," says Alan, presently Interim Associate Dean for Research. In addition, the team of High, Tree, and High are exploring the applicability of strong-acid polymer catalysts for the synthesis of liquid organic molecules from gases.

Research on particle properties and size development is led by Professors "AJ" Johannes and Gary Foutch. They are using computational fluid dynamics programs and kinetic models of interfacial mass transfer and chemical reaction to improve the design of reactors.

We have forty graduate students, averaging about four per faculty member, and each faculty member has externally sponsored research. All graduate students are supported, and 60% are PhD candidates. The faculty backgrounds and research interests are shown in Table I.

ATTRACTIVENESS OF THE AREA

"I sought a place where I could build a future for both my career and my family. OSU gave me collaborative faculty, and Stillwater gave me a great place to live," says biomedical expert Randy Lewis. He notes that the quality of life in Stillwater, a town with about 35,000 permanent residents, has the flavor of a small town but is only a little over an hour from either Tulsa or Oklahoma City. With a temperate climate and located in the rolling hills of "green country," there are four balanced seasons and many local recreational opportunities. Ken Bell adds, "The beauty of the campus originally attracted me to OSU, and the recent upgrades in the Student Union gardens and Theta Pond have made it even better."

There are 250 undergraduates who have declared chemical engineering as their major. About one third of them are female, about 15% are from minority groups, and about 20% are from outside of the state. These statistics allow everyone to have an extended family of diverse individuals. Upper-level class sizes are about 35; thus, with a faculty size of eleven, the student-to-faculty ratio is relatively low.

With about 19,000 students on the Stillwater campus, OSU is large enough to offer a broad variety of classes and a wide range of student activities: Big XII athletics, cultural events, international student societies, intramural events, recreational outings, and study groups. The "engineering floors" in the dorms provide both social and academic support activities for the students.

OPPORTUNITIES

For freshman and Phillips Scholar Christy Petersen, "Opportunities made the program attractive." She should know. Her older sister is a senior, and her oldest sister and brother-in-law are recent graduates, all from chemical engineering at Oklahoma State. "The program prepares students for a broad range of careers. Carl is in law school, Tracie is enjoying her industry assignments, and Jill is looking at medical school. Within chemical engineering we have the bioengineering, premedical, and environmental options. And, while on campus, there are many activities that allow us to explore our potential." Hosting the 1999 National AIChE Annual Student Conference in Dallas, Texas, was a major activity that engaged about 50 of our students.

One of the special features of the College of Engineering, Architecture, and Technology is that all students are in a "common" curriculum for their first two years. Once they qualify academically, they are admitted into the School that offers a degree in the major of their choice. Courses in the common engineering curriculum include computer programming, statics, thermodynamics, fluid dynamics, strength of materials, electrical circuits, and materials science. Faculty from separate Schools team-teach most of these courses, and their content is controlled by the faculty from all disciplines that require the courses. This means that chemical engineering students get a multidisciplinary perspective in their general engineering courses, and as a result, they have subsequent career flexibility. Course management by an oversight committee maintains a balanced structure, curriculum content, and high academic standards. This broad and quality-monitored experience contributes to diverse career opportunities for the students.

Students have to qualify for acceptance into the School of Chemical Engineering. Making the "grades" in the first two years is a prerequisite to taking the upper level chemical engineering courses. It is a significant challenge, and the feeling is that the student-faculty family is an important contributor for promoting academic scholarship and encouragement.

Undergraduates can be involved in research if they wish to explore outside of the classroom. Recently, Nellie Bruce, a junior, received a Wentz Scholarship to develop an artificial kidney experiment that will be used for the newly developed biomedical engineering course. Nellie is the fourth of her siblings to choose engineering at OSU and the third in chemical engineering. Dipesh Pokharel received a Wentz Scholarship to study the effects of nitric oxide (NO) on smooth muscle-cell growth. Dipesh developed the experimental apparatus that delivers controlled and predictable amounts of NO to a culture dish containing smooth muscle cells. Cell growth is monitored during NO exposure. Phoebe Brown, recipient of a national Morris Udall Scholarship, is evaluating a method for automatic identification of steady state in multivariable processes. Since most processes generate noisy data, the method is statistically based. Phoebe is testing the multivariable method on data from the Unit Operations Lab distillation column.

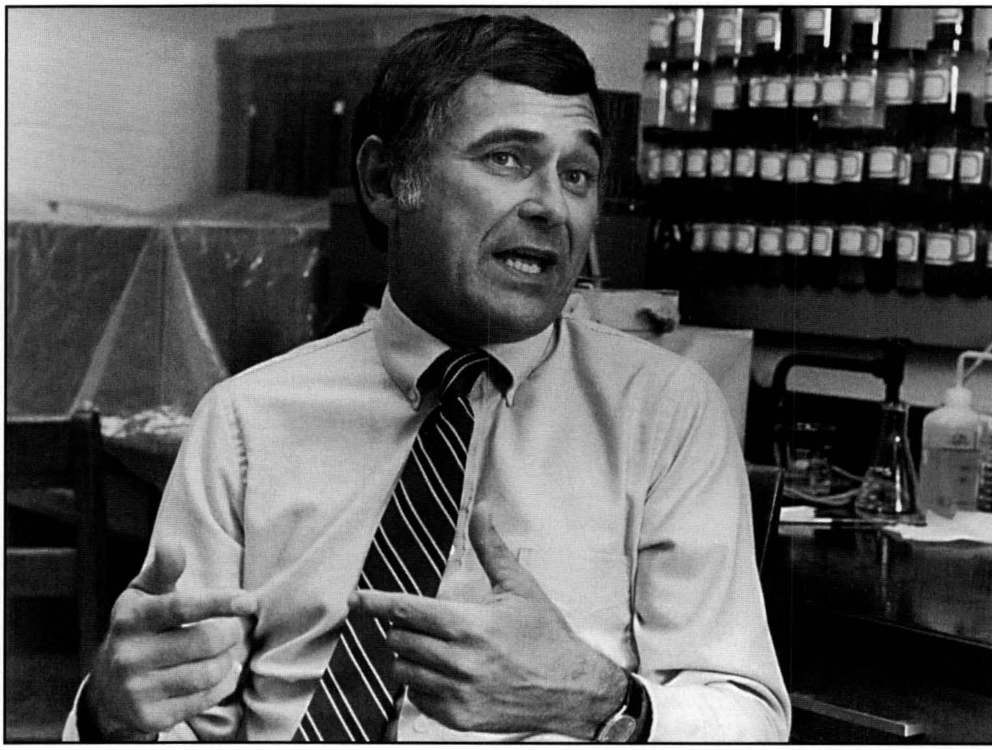
MAGIC?

Chemical engineering at OSU uses the same textbooks as other universities. It is accredited by the same rules. It has the same best students. It has the same inadequate operating budget. It has the same web and library access. So—what is the reason for its success? If not magic, then it must be a shared commitment to human development and a focus on getting results in the real world.

We invite you to enjoy a visit to our web pages at http://www.cheng.okstate.edu. ❒

Don Green

of the University of Kansas



PRISELLA J. ADAMS
University of Kansas • Lawrence, KS 66045

When Don Green entered graduate school in the late 1950s, he didn't know that he would emerge with a lifelong friendship and professional relationship that would affect how chemical engineers the world over do their jobs. *Perry's Chemical Engineers' Handbook*—relied on by practicing engineers and engineering students alike—has a history few people know. Fewer still understand the role Don Green has had in continuing the Perry family legacy.

"I was Bob Perry's first PhD student when he was a chemical engineering faculty member at the University of Oklahoma," recalls Green, who is the Deane E. Ackers Distinguished Professor of chemical and petroleum engineering at The University of Kansas. "John Perry [Bob's father] edited the first three editions, and Bob assumed editorship after his father's death in 1953. While at OU, Bob edited the fourth edition of the handbook, and I assisted him in various ways, including working on the kinetics section."

The Green and Perry families continued their friendship after both men left OU. In 1977, Perry was consulting and living in London while continuing his work with the handbook, and he pressed Green into service again.

"Bob invited me to be a section editor on the sixth edition and had a plan that I would join him as coeditor for the seventh edition, targeted for publication about ten years after the sixth," Green said. "Bob had two sons, neither of whom had careers related to engineering. He had inherited the book from his father, and I think he wanted to pass the leadership along to a person who was close to him and almost like family."

Green accepted the invitation, but before the two friends were able to do much work, Bob Perry was killed instantly in a tragic car accident in London while crossing the street on foot. Perry's widow, Gail, and publisher of the handbook, McGraw-Hill Book Co., asked Green to assume the editorship of the sixth edition, and he accepted. Green engaged James O. Maloney, KU emeritus professor of chemical and petroleum engineering and former department chairman of 19 years, to support the project as assistant editor. The sixth edition sold approximately 190,000 copies and is probably more widely distributed across the world than any other chemical engineering book.

► *"Don [comes] across as a caring and thoughtful person, one who [embodies] the philosophy that the university experience can transform the lives of students. . . . [He] is an excellent role model for other faculty in that he does everything so well: teaching, scholarship. leadership, and service. And he excels in all of these areas while maintaining a calm, cool demeanor."* ◄

Today, *Perry's Chemical Engineers' Handbook* is in its seventh edition, with Don Green as editor and J.O. Maloney as associate editor. Published in 1997, it has sold approximately 37,500 copies in its first two years and was recognized by the Library Division of the American Society for Engineering Education as the Best Reference Book of 1998.

Bob Perry's decision to pass his father's legacy on to Green was well-founded. Don Green is an inspired educator and esteemed research engineer who holds genuine concern for the success and happiness of his students and colleagues. He is a well-known researcher in oil reservoir technology, a Fellow in the American Institute of Chemical Engineers, and an ABET accreditation visitor for the Society of Petroleum Engineers (SPE). He is a Distinguished Member of the SPE, a reviewer of technical articles for the SPE Journal, and has been an SPE Distinguished Lecturer. Green is chairman of his department at KU and past chair of the Association of Petroleum Engineering Heads. He is a sports enthusiast and a faculty athletic representative to the Big XII Conference and the National Collegiate Athletic Association. But his role of professor as teacher is the role Green loves best. During a 35-year teaching career, he has inspired countless students with his enthusiasm, dedication, judgment, and good nature.

"Don made his class subject matter interesting and enjoyable," says former student Bill Weisenborn, now with Conoco, Inc. "He could explain all topics in such a way that we wanted to continue to learn and improve ourselves."

Carlos Rocha, former graduate student and now a project manager with Jacobs Engineering in Hamilton, Ohio, finds that he still calls upon advice gained in Green's classes. "Don Green provided me with an example of how a person should behave in our competing and demanding society," Rocha says. "As a project manager for a very large engineering consulting firm, sometimes I get caught on decisions that I think are overwhelming. How can I make the right decision—do the right thing? I go back to what I learned from Don: If I am not uncomfortable telling my family the decision I made and its potential consequences, then I made the best decision I could. He taught me ethics as an engineer and as a human being."

EARLY, EASY DECISIONS

Green was born and raised in Tulsa, Oklahoma, when the city bore the nickname of "Oil Capital of the World." Oil derricks and office buildings of the world's largest petroleum companies neighbored the American Legion ball fields that Green played on as a boy. In a community with an industry based in petroleum, Green never questioned having a career in oil. He decided during high school to become a petroleum engineer.

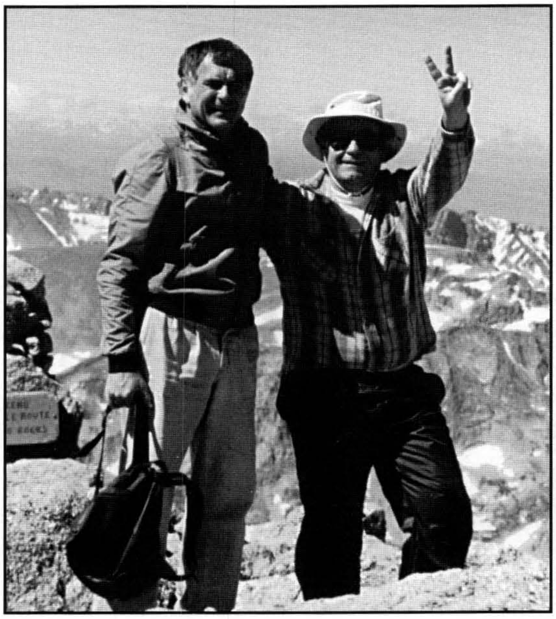
Green spent his freshman year at Oklahoma State University before transferring to the University of Tulsa. His love for baseball won him the varsity team's third-base position for two years, and he was selected as second-team All-American. In 1954, Green and Patricia Polston, who was studying nursing, were married. The next year, Green graduated with a BS in petroleum engineering and went to work as an engineer trainee for Gulf Oil Co., in Tulsa.

Having participated in an Air Force ROTC program as an undergraduate, Green was called into active duty after five months at Gulf Oil. Point of duty: Suffolk County AFB, Long Island, New York.

"Being a Midwesterner, the East Coast was the last place in the world I wanted to be stationed," Green says, "but it turned out to be a great location and assignment."

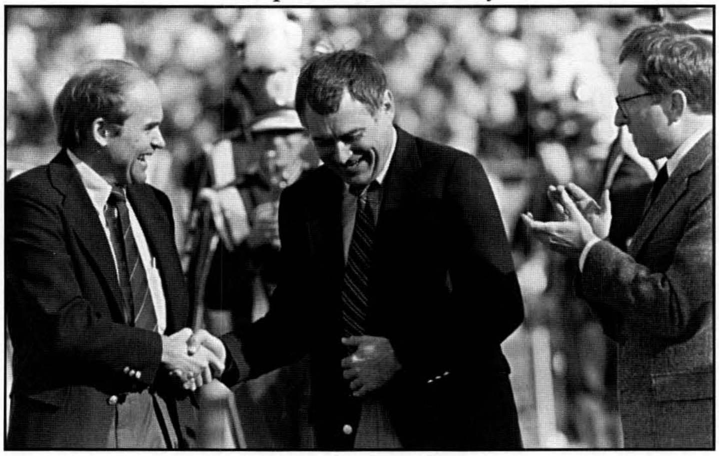
Green was made petroleum supply officer for the base, a position of responsibility that honed his management skills and gave him the maturity to think clearly about the future. He settled on returning to school for graduate study in chemical engineering, and in 1958 he and Pat traveled back to Oklahoma. Green entered the master's program at the University of Oklahoma under Professor Richard Huntington. He continued at OU as a doctoral student under Professor Perry.

Still pursuing his interest in petroleum engineering, Green chose heat transfer in porous media as his doctoral research topic. He considers his excellent experience as a doctoral student to have been a strong influence on his decision to become a professor. Mentors that influenced



◀ ***Don (left) and his brother-in-law Bob Willett at the top of Long's Peak in Rocky Mountain National Park, Colorado, after scaling the 14,256-ft. mountain.*** *(Photo courtesy of Don Green, 1994)*

▼ ***C.S. Howat, III (left) congratulates Don on receiving the 1987 HOPE Award while chancellor Gene Budig (right) looks on. Howat and Green are both on the faculty of the KU Chemical and Petroleum Engineering Department.*** *(Photo by R. Steve Dick, 1987)*



him most were Perry, Cedomir Sliepcievich, and Jack Powers.

Green finished his doctorate in 1962 and joined Continental Oil Company. As a research engineer in the company's Petroleum Production Research Division in Ponca City, Oklahoma, Green worked with computer simulations of oil reservoirs. Although the research was challenging, Green's graduate school experience remained in his thoughts.

"The lifestyle the professors were leading seemed exciting to me," Green says. "I liked the idea of being in a university setting where teaching, research, and scholarship activities were combined."

After two years in industry, Green made the move to being a chemical and petroleum engineering educator when he was hired by KU in 1964 as an assistant professor. Because the chemical and petroleum engineering department at KU offered undergraduate and graduate degrees in both areas, Green and the job were a perfect fit. He was promoted to associate professor in 1967 and to full professor in 1971. He was named the Conger-Gabel Distinguished Professor in 1982, an award that requires a demonstrated record of sustained excellence in undergraduate education in addition to excellence in research and professional service. And in 1995, Green was honored with the Deane E. Ackers Distinguished Professorship, a post he still holds.

He is in his second term as department chairman and has won teaching awards on the average of one every other year. With his KU colleague Paul Willhite, Green is co-director of a program in oil reservoir technology that is recognized as a model for technology transfer.

AN EXEMPLARY TECHNOLOGY TRANSFER PROGRAM

From its location in the state's eastern corner, The University of Kansas has long been considered by state residents, whether for better or worse, as a liberal institution. The political atmosphere of the Vietnam era only added to that reputation. While student demonstrations at KU did not escalate to the levels of violence at other universities across the country, KU's image statewide was somewhat tarnished.

In 1973, then-Chancellor Archie Dykes pushed the university to develop interactive programs with the state. Green and Willhite took a close look at Kansas oil producers, who at the time were between a rock and a hard place: The country was enduring an energy crunch, yet within Kansas bedrock lay inaccessible oil resources. The producers, who were mostly small, independent operators without engineering staffs or direct access to research facilities, found themselves unable to use the enhanced oil recovery technology being developed primarily by major oil companies. Green and Willhite responded with a concept for a program that would help the state's independent oil producers take advantage of technology research that no single producer could afford to fund.

The Tertiary Oil Recovery Project (TORP) received state funding in 1974, with Green and Willhite as co-directors. It has been funded every year since and last fiscal year received more than $790,000 in research support from the State of Kansas. Since 1979, the U.S. Department of Energy has provided more than $8.5 million in support of research and technology transfer. Major companies such as AMOCO, Phillips Petroleum, and Marathon Oil have also been supporters. The project's objectives are to conduct research related to enhanced oil recovery processes, to provide technical assistance to industry, and to educate students and operators in tertiary oil recovery and reservoir management. TORP is tied closely to the CPE department and to the KU School of Engineering. Over the years, about 90 graduate students have conducted research through TORP leading to their PhD or MS degree. The project has also provided research opportunities for undergraduate students.

Green and Willhite have published numerous articles and reports related to oil recovery, and they are frequent presenters at technical meetings. In 1998, they published *Enhanced Oil Recovery* through the Society of Petroleum Engineers. The book is a comprehensive text of advanced oil-recovery processes and is applicable for use in senior or graduate courses in petroleum engineering.

Over the years, TORP researchers have explored thermal recovery processes, micellar-polymer flooding, carbon dioxide miscible displacement, reservoir computer simulation, and in situ permeability modification using gelled polymer systems.

A major, current emphasis is development of gelled polymer technology, which aims to improve volumetric sweep efficiency in oil-recovery displacement processes such as waterflooding. In such a displacement process, the injected fluid often flows between the injection wells to production wells in a "short circuit" because of high permeability zones or fractures in the reservoir. As a result, most of the oil is bypassed and not contacted by the injected fluid, resulting in poor displacement efficiency. Additionally, the injected fluid must be recirculated or disposed of, which can be costly. Gelled polymer technology involves injecting a gel system into the "thief" zone where it reacts to form a gel and thereby seals off the zone. Fluid subsequently injected will be forced into other parts of the reservoir, thereby improving efficiency.

> ***"I strongly feel that what is right for our program is a balance between teaching and research that gives each a comparable weighting," Green says. "I think that one of my primary roles as chair is to support the faculty in every appropriate and feasible way.***

TORP researchers also are working on implementing a field trial to recover oil from Kansas reservoirs through applications of supercritical carbon dioxide. They believe the process, which has been used successfully in west Texas, has the potential to revitalize the Kansas oil industry. To gain an understanding of the potential impact the field trial may have, approximately 10 billion barrels of unrecovered oil are estimated to lie within Kansas' borders.

The success of TORP at transferring viable technologies into the private sector has gained the program recognition by the Independent Petroleum Association of America and by the Department of Energy. Because TORP was an early participant in technology transfer and because the project has been so effective in fulfilling its objectives, the Department of Energy used TORP as a model when it increased funding of tech-transfer programs across the country in 1994.

MAKING A STRONG DEPARTMENT STRONGER

TORP is one of several research programs that involve KU's chemical and petroleum engineering students. The department has had a rotating chair since 1964, and since then Green has held the post twice, including his current appointment. Green credits Willhite, the department's previous chair, with building a well-rounded faculty and with strengthening the research programs. Both are areas Green continues to emphasize.

"I strongly feel that what is right for our program is a balance between teaching and research that gives each a comparable weighting," Green says. "I think that one of my primary roles as chair is to support the faculty in every appropriate and feasible way. This means providing the resources needed for teaching, assisting in the development of research programs, and working to see that they are recognized for accomplishments."

The result is a cohesive department with a diverse faculty, strong undergraduate and graduate programs, and well-endowed scholarships that attract some of the brightest students entering the university. A recent review of the university by the Kansas Board of Regents provided data showing that the average ACT score of freshmen entering the CPE program was the highest of any program at KU.

Compared with their peers nationally, KU's CPE students remain strong. In the last fifteen years, KU students have won more awards in the National Student Design Competition sponsored by the AIChE than any institution in the country. The record is due in large part to Sharp Teaching Professor Colin S. Howat III, who teaches chemical engineering design, as well as to the outstanding quality of the student body.

Student achievements in the last two years have brought the department further national recognition. In 1998, three chemical engineering students were awarded Barry S. Goldwater scholarships for outstanding academic achievement and research. The honor, considered the premier award of its type, is given annually to undergraduates who excel in engineering, natural sciences, or mathematics. An institution may nominate only four students. Interestingly, that year a

KU physics student also won a Goldwater Scholarship, so the university as a whole was batting four for four.

One of the chemical engineering recipients, Larissa Lee, went on to win a Churchill Foundation Scholarship to study in England. Lee pursued the department's pre-medical option, one of three program options that Green and CPE faculty developed to enable undergraduate students to tailor their studies according to their plans for graduate school or industry. The options are pre-medical, biomedical, and environmental.

The program options, combined with strong scholarships, have attracted greater numbers of women students to the CPE program. In the 1997-98 school year, nearly 46% of undergraduate degrees in chemical engineering at KU were awarded to women. The average throughout the School of Engineering, which has ten undergraduate engineering programs, was 19.2%. Nationally, the figure for women earning undergraduate degrees in engineering was 18.7% according to the American Association of Engineering Societies, Inc.

As chair, Green has worked to maintain excellence in teaching and research innovations by building faculty strength. The department recently hired three new faculty, two of whom are women, to make a total of thirteen members. Bala Subramaniam, Conger-Gabel Distinguished Professor and assistant department chair, notes that Green is the type of leader who considers all viewpoints, yet arrives at decisions without delay. "Don's impressive record of accomplishments in education, research, and service enables him to command the respect and trust of his faculty as chair," Subramaniam says. "I've found Don to be a very open-minded leader, and he has a knack for developing consensus."

Marylee Southard, an alumna of the chemical engineering program and now an associate professor, says Green encourages everyone to go as far as possible to reach their own potential. "He is the ultimate cheerleader," she says, offering as example Green's support when both educators were in contention for a university-wide teaching award. "We stood out on the football field at halftime on a typical sunny, chilly November day, waiting for the winner to be announced. Don commented to me that he hoped I'd win it; that he'd already won this once before, and I deserved it. When it happened, I believed him."

Subramaniam echoes Southard's observations. "Don believes that an important role of a chair is to facilitate the professional development of every faculty member. He does this fairly and effectively. I have been most impressed by his genuine concern to see every one of his faculty succeed and be suitably rewarded for their efforts."

Southard considers Green's most significant achievement to be a consistency of excellence that affects how he mentors both students and faculty. "He has lived what he advises us 'young Turks' to do," Southard says. "Don is committed to doing the best at all facets of his job. He is tireless in his work and completely prepared for meetings and classes every day."

Green also has been involved with the KU Athletic Department [and] serve[s] as the university's Faculty Athletic Representative to the Big XII Conference and the NCAA [where he] deals with legislative issues such as academic requirements, rule-waiver requests, eligibility concerns, and budgets.

TREATING STUDENTS AS JUNIOR COLLEAGUES

Subramaniam says that whether Green is teaching an introductory class to freshmen or a graduate-level special-topic seminar, he prepares his lecture with the audience in mind and delivers the lecture with the same enthusiasm and clarity. "This is just a reflection of Don's positive attitude toward, and respect for, students at all stages," Subramaniam says. "He treats them all alike—as junior colleagues, as he likes to say."

Tom Edgar, chaired professor of chemical engineering at the University of Texas, says his interaction with Don Green while a student at KU in the late 1960s was a major factor in his decision to become an educator. "Don came across as a caring and thoughtful person, one who embodied the philosophy that the university experience can transform the lives of students," Edgar says. "Don is an excellent role model for other faculty in that he does everything so well: teaching, scholarship, leadership, and service. And he excels in all of these areas while maintaining a calm, cool demeanor."

"Those of us who go through cycles of burnout and high energy wish there were a pill that could give us his drive," Southard says. But the answer to Green's energy lies with his mentor, Bob Perry. Green says, "Bob used to tell me, when things were not going all that well because of administrative or bureaucratic problems, 'Thank God for the students. It's because of the students that we're here.' That quote accurately reflects my feelings."

His sense of humor no doubt has helped Green keep his energy level high, particularly when he uses it in classroom settings to ease tension and let students know that he, too, is human. Rocha remembers Green as capable of taking jokes and handling unforeseen situations well. "In one of his courses, he gave us (the students) the wrong data to use in a computer problem. He showed up in the classroom with a sign hanging from his neck that read 'Stupid.'" Rocha continues, "He taught me that we all make mistakes, even a professor, and that it makes the situation much better for everybody if the mistake is acknowledged and everyone moves forward together."

Over the years, Green has won numerous teaching awards, but the award of which he is most proud is the university-wide Honor to Outstanding Progressive Educator, or HOPE, award. The award selection is made annually by members of the senior class.

Green was the initial sponsor of the precursor to the KU student chapter of the Society of Women Engineers, and he has involved himself in other campus programs related to students and teaching. In the 1970s, Green and his colleague, Floyd Preston, worked with a group of African American students to develop a program to recruit, support, and mentor undergraduates. Preston and Green were the first sponsors of the group, and over the years it has evolved into a well-established program that incorporates four minority engineering groups. It now has a full-time adviser and serves approximately eighty students at any one time.

(Left to Right) Don, his daughter-in-law Aina, his son Guy holding granddaughter Erika, his wife Pat, his son Patrick, and his son Michael.

Green also has been involved with the KU Athletic Department, serving two terms on the athletic board. In 1996, Chancellor Robert Hemenway invited Green to serve as the university's Faculty Athletic Representative to the Big XII Conference and the NCAA. In the post, Green deals with legislative issues such as academic requirements, rule-waiver requests, eligibility concerns, and budgets.

Several years ago Don took part in a university-wide discussion of teaching. The result was a committee that focused on ways of improving teaching and undergraduate education. Green chaired the committee for several years, during which it looked at issues such as colleague-to-colleague mentoring, improving classroom physical facilities, augmenting audio-visual equipment in classrooms, holding teaching colloquia, and initiating teaching awards. The committee evolved into the Center for Teaching Excellence at KU and now has its own facility and dedicated staff.

AWAY FROM THE CLASSROOM

Don Green may not allow his competitiveness to come through when teaching, but he is only holding it in check. An avid handball player since his days in graduate school, he rarely lets anything interfere with his games and often plays three times a week with a small group of friends. "We feel about handball as does Sarge of the 'Beetle Bailey' comic strip," Green says. "According to Sarge, handball is the only real court game and racquetball is for wimps. At least, that's the kidding I give to our students, who tend to play racquetball."

Green and his three sons, all KU graduates, are enthusiastic about KU sports, especially KU basketball. Guy, the oldest son, is an environmental engineer with the U.S. Corps of Engineers, Michael is Assistant U.S. Attorney in the Western District of Missouri, where he prosecutes drug cases, and Patrick is a medical doctor and cardiologist in Ft. Collins, Colorado. Pat and Don are blessed with two grandchildren, ages seven and four, who were born to Guy and his wife, Aina.

When his sons were young, Green served as Little League coach, and the family often went camping and hiking together, something they still enjoy. The family shares a vacation home near Estes Park, Colorado. Green has climbed Long's Peak, in Rocky Mountain National Park, three times—twice with Pat. The mountain, known as a "fourteener" by climbers, has an elevation of 14,256 feet and an elevation gain of 4,850 feet. Green plans to go to the top again soon. "When you're hiking, you're challenging yourself and you get to see beautiful country," he says. "Being outdoors is wonderful, and there's nothing like being in the mountains."

The drive to challenge oneself and others from a point of respect while at the same time enjoying life is a gift Don shares with those around him. Marylee Southard, who first met Don in 1972 when she was a senior in high school, characterizes him best. "Don said he has no recollection of any childhood pivotal point or transforming cataclysm that suddenly gave him drive and optimism," she says. "I believe these traits are an inborn part of Don Green. He is a Midwesterner with a decent work ethic and a love for his students and for working with them. We who have been mentored by Don are his legacy, and we hope that his attitude and energy have become part of us as we talk and work with him." ❐

THE FUTURE OF ENGINEERING EDUCATION

Introduction to a Series

Richard M. Felder
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In the Spring 1990 semester, I spent a most enjoyable sabbatical semester at Georgia Tech, where I worked with Ron Rousseau on the initial stages of the revision of *Elementary Principles of Chemical Processes.* At the same time, I was wading through a mountain of books and papers on cognitive psychology, educational psychology, and science and engineering education, building up my background for a longitudinal study of engineering education for which the NSF had just provided funding.

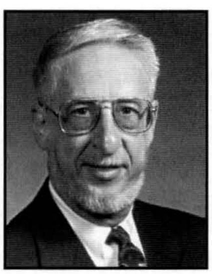
The research I was immersed in led me to several observations. First, there was a lot of stuff out there in the literature, some of which I found particularly relevant to my courses and my students. Second, few engineering professors would ever have the time or inclination to wade through all of it in search of something they could use. It occurred to me that as long as I was going through the exercise of distilling the literature, it might be useful to my colleagues if I shared the fruits of my labors. It also occurred that it would make little sense for me to do it alone, since I knew of other engineering educators who had thought about these issues far more than I had and had a much deeper knowledge of the literature.

At that point I conceived of a series of survey articles in *Chemical Engineering Education,* coauthored by highly knowledgeable educators with me riding their coattails. Among the most knowledgeable chemical engineering educators I knew at the time—and still among the most knowledgeable—were (in alphabetical order) Armando Rugarcia of the Universidad Iberoamericana in Mexico, Jim Stice of the University of Texas, and Don Woods of McMaster University in Canada. I invited them to participate and was delighted when all three accepted. The North American quartet got to work immediately.

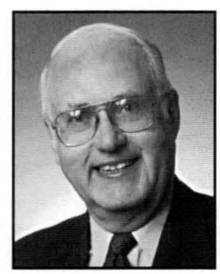
Then life happened.

Armando became Rector of his university, Jim started running all over the country giving teaching workshops, and Don became a self-contained book-of-the-month club as his problem-based learning approach became an international paradigm for effective instruction. Also, owing to the incessant time demands of the book revision, the longitudinal study, and my own teaching workshops, I became the worst offender of all. But at length we picked it up again, thanks mostly to Don's unflagging energy and initiative, and the series finally came into existence.

The first two papers follow in this issue, and the remaining four will appear in subsequent issues. The first paper sets the stage and previews the structure of the series, so I won't do so here. I will just say that it has been a privilege and pleasure to work with such outstanding educators and good friends as my coauthors. I have been inspired by their ideas for many years. I hope their enthusiasm and love of their work comes through in these papers and inspires the readers in the same way. ❒

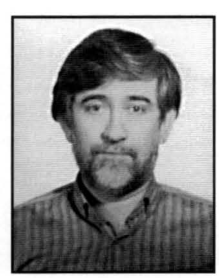


***Richard M. Felder** is Hoechst Celanese Professor (Emeritus) of Chemical Engineering at North Carolina State University. He received his BChE from City College of New York and his PhD from Princeton. He has presented courses on chemical engineering principles, reactor design, process optimization, and effective teaching to various American and foreign industries and institutions. He is coauthor of the text* Elementary Principles of Chemical Processes *(Wiley, 2000).*



***Donald R. Woods** is a professor of chemical engineering at McMaster University. He is a graduate of Queen's University and the University of Wisconsin. He joined the faculty at McMaster University in 1964 after working in industry, and has served as Department Chair and as Director of the Engineering and Management program there. His teaching and research interests are in surface phenomena, plant design, cost estimation, and developing problem-solving skills.*

***James Stice** is Bob R. Dorsey Professor of Engineering (Emeritus) at the University of Texas at Austin. He received his BS degree from the University of Arkansas and his MS and PhD degrees from Illinois Institute of Technology, all in chemical engineering. He has taught chemical engineering for 44 years at the University of Arkansas, Illinois Tech, the University of Texas, and the University of Wyoming. At UT he was the director of the Bureau of Engineering Teaching and initiated the campus-wide Center for Teaching Effectiveness, which he directed for 16 years.*



***Armando Rugarcia** graduated from the Universidad Iberoamericana (UIA) in 1970 and went on to earn his MS in chemical engineering from the University of Wisconsin in 1973 and his Doctorate in Education from West Virginia University in 1985. He has been a full-time professor of engineering at UIA since 1974 and was chair of the Chemical Engineering Department there from 1975 to 1980. He was also Director of the Center for Teaching Effectiveness at UIA from 1980 until 1986. He has written four books on education, one on process engineering, and more than 130 articles.*

THE FUTURE OF ENGINEERING EDUCATION

Part 1. A Vision for a New Century

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When we walk into an arbitrarily chosen engineering classroom in 2000, what do we see? Too often the same thing we would have seen in 1970, or 1940. The professor stands at the front of the room, copying a derivation from his notes onto the board and repeating aloud what he writes. The students sit passively, copying from the board, reading, working on homework from another class, or daydreaming. Once in a while the professor asks a question: the student in the front row who feels compelled to answer almost every question may respond, and the others simply avoid eye contact with the professor until the awkward moment passes. At the end of the class, students are assigned several problems that require them to do something similar to what the professor just did or simply to solve the derived formula for some variable from given values of other variables. The next class is the same, and so is the next one, and the one after that.

There are some differences from thirty years ago, of course. The homework assignments require the use of calculators instead of slide rules, or possibly computers used as large calculators. The math is more sophisticated and graphical solution methods are not as likely to come up. The board is green or white, or maybe an overhead projector is used. Nevertheless, little evidence of anything that has appeared in articles and conferences on engineering education in the past half-century can be found in most of our classrooms and textbooks.

...increasing numbers of university administrators and professors . . . question the viability of the way engineering has traditionally been taught, and some have begun to explore alternatives. . . . even those who know about alternatives fear that transforming the way they teach will require a full-time commitment that will leave them with insufficient time to pursue their research.

In recent years, however, there have been signs of change.[1] Engineering professors have increasingly begun to read the education literature and to attend ASEE conferences and teaching workshops, and some have attempted to adopt new approaches in their teaching. A number of factors are responsible for this increased interest in effective teaching in engineering schools. Growing numbers of parents, taxpayers, and legislators have read graphic descriptions of the de-emphasis of undergraduate education at major universities[2] and have begun to raise embarrassing questions with university administrators. Corporations and employers have frequently and publicly complained about the lack of professional awareness and low levels of communication and teamwork skills in engineering graduates[3-6] and about the failure of universities to use sound management principles in their operations.[7,8]

These rumblings have been heard by the U.S. Accreditation Board for Engineering and Technology (ABET), which now proposes to hold engineering schools accountable for the knowledge, skills, and professional values engineering students acquire (or fail to acquire) in the course of their education. Starting in 2001, Engineering Criteria 2000 will be implemented as the standard for accreditation. Thereafter, all U.S. engineering programs will have to demonstrate that besides having a firm grasp of science, mathematics, and engineering fundamentals, their graduates possess communication, multidisciplinary teamwork, and lifelong learning skills and awareness of social and ethical considerations associated with the engineering profession.[9]

These driving forces and personal convictions about the importance of education in the academic mission have led increasing numbers of university administrators and professors to question the viability of the way engineering has traditionally been taught, and some have begun to explore alternatives. Most, however, are unsure of what the alternatives are to the traditional methods, and even those who know about alternatives fear that transforming the way they teach will require a full-time commitment that will leave them with insufficient time to pursue their research.

Our goal in this paper and in the five that follow it is to offer some tools to engineering professors who wish to become better teachers and to university administrators who wish to improve the quality of teaching at their institutions. This paper attempts to define in some detail the challenges currently facing engineering education. The second article will survey teaching methods that have repeatedly been shown to improve learning; the third will elaborate on methods that help students develop critical skills; the fourth will examine effective ways to prepare the professoriate to learn and implement the new methods; the fifth will propose methods of assessing and evaluating teaching effectiveness; and the sixth will explore possible modifications in the university incentive-and-reward structure that will enable the desired changes to occur on a systemic level.

THE TECHNOLOGICAL PERSONALITY OF THE 21ST CENTURY

A system of education is closely woven into the fabric of the society within which it operates. Before examining new ways to train engineers, we might do well to anticipate some characteristics of the society within which the engineers we are training will function. We are writing from the perspective of Mexican, American, and Canadian cultures, but we feel that the trends can be generalized to a broad range of developed and developing nations.

We see seven features of the coming century that will pose challenges to future engineers.

- ***Information:*** *Proliferating* • In 1989, 10,000 volumes were required just to list the titles of all the books that had been published, and roughly 6,000 scientific articles were published every day.[10] The number of documents available has since tripled, and there is every indication that the rate of growth will be sustained, if not increased. Moreover, the flood of information will wash right up to the engineer's fingertips through the internet, virtual environments, and CD-ROM discs that can each hold up to one million pages of text.
- ***Technological Development:*** *Multi-disciplinary* • In the early part of this century, engineering practice could be classified along disciplinary lines (although not to the extent that university curricula would have had us believe). The body of knowledge that constituted the working arsenal of, say, a chemical engineer, was well-defined and distinct from that which characterized a mechanical or electrical engineer or a chemist or physicist. The situation now is much more complex: for example, engineers of all types are finding themselves faced with a need to know electronics and/or biochemistry. The key to better technological development lies in cooperation among the previously separate disciplines to attack problems that have no recognizable disciplinary boundaries.
- ***Markets:*** *Globalized* • In the future, industries that cannot compete in the international market are unlikely to survive in the domestic market. Succeeding internationally requires cultural and economic understanding no less than technological expertise.
- ***The Environment:*** *Endangered* • Producing more in order to earn more will no longer be the sole paradigm of industry. The threats to quality of life resulting from unrestrained environmental depredations and the depletion of nonrenewable resources are sources of growing concern, even within industry. In addition to quality and productivity, industry will require that profitability be achieved within a context of not harming people or their habitat. Increasingly, industries are adopting "The Natural Step" process (TNS) or an equivalent to guide their decision making about the global use of the world's resources.[11,12] The four principles of TNS are

1. Substances extracted from the earth's

The key to better technological development lies in cooperation among the previously separate disciplines to attack problems that have no recognizable disciplinary boundaries.

crust (such as oil, fossil fuels, metals, and other minerals) must not systematically accumulate in the ecosphere. That is, the rate of mining from the earth's crust must not occur at a pace faster than the extracted species can be redeposited and reintegrated into the earth's crust.

2. *Substances produced by society must not systematically increase in the ecosphere. That is, synthetic substances must not be produced at a rate faster than they can be broken down and integrated into natural cycles.*
3. *The physical conditions for productivity and assimilation within the ecosystem cannot be systematically diminished. Forests, wetlands, prime agricultural land, natural plants, and animals cannot be systematically destroyed.*
4. *Since resources are limited, basic human needs must be met with the most resource-efficient methods available. Industrialized nations cannot use the resources to create luxuries while the basic needs of people in underdeveloped nations are not being met.*

► ***Social Responsibility:*** *Emerging* • Technology is responsible for much of what we value about our society and our way of life, but it must also take responsibility for the threats to public health and the depletion of nonrenewable natural resources that now endanger that way of life. The historical thrust of technological development has been to increase consumption and profit; we are falling well short of where we should be in our ability to provide adequate health care, efficient public transportation, affordable housing, and quality education for all citizens. We are not bridging the gap between the technologically advanced societies and those that do not have even the basic means for survival. While the origins of many of these problems may be political rather than technological, it is up to scientists and engineers to participate in the decision-making processes to a greater extent than ever before. We have obligations to inform ourselves and the rest of the population about the potential social consequences of the decisions that are made, to judge whether the implementation of decisions is consistent with the objective of technology to improve our well-being for citizens of the world (as outlined in TNS principle #4), and to take appropriate action or choose inaction, depending on the outcome of the judgment. Acceptance of this social responsibility by industry and individual engineers is a necessary step for the survival of our society in the next century. A corporate culture consistent with the four principles of TNS, or equivalent, is needed.

► ***Corporate Structures:*** *Participatory* • Companies in different societies are moving toward structures that allow for greater participation of individuals in the decision-making process. Quality circles, small-group planning, and troubleshooting sessions with joint participation by management, technical, and operational staff are increasingly common. Layers of middle management have been eliminated, with much of the decision-making power being transferred downward to a broader spectrum of the corporate body. Individual employees are acquiring to an increasing extent the right to take part in decisions that relate to their jobs and to assume responsibility for the consequences of those decisions.

► ***Change:*** *Rapid* • Changes of a magnitude that not long ago would have taken years now occur on a time scale of months or weeks, as anyone who purchased a computer over one year ago realizes. Curricula that attempt to remain current with industrial practice by continually providing courses in the "new technology" are likely to be ineffective. By the time the need is identified, the courses developed, and the students trained, the new technology has changed. The education that succeeds will be the one that facilitates lifelong learning, equipping students with the skills they will need to adapt to change.

COMPONENTS OF ENGINEERING EDUCATION

What can we say about the individuals needed to function as engineers in the society whose technological characteristics we have just outlined? Their profiles may be conveniently sketched in terms of three components: (1) their *knowledge*—the facts they know and concepts they understand; (2) the *skills* they use in managing and applying their knowledge, such as computation, experimentation, analysis, synthesis/design, evaluation, communication, leadership, and teamwork; (3) the *attitudes* that dictate the goals toward which their skills and knowledge are directed—personal values, concerns, preferences, and biases. Knowledge is the data base of a professional engineer; skills are the tools used to manipulate the knowledge in order to meet a goal dictated or strongly influenced by attitudes.

In its early years, engineering education did a good job of transmitting knowledge to engineering students, and it might be argued that it facilitated the development of skills and promoted values in ways appropriate for the time. Until about thirty years ago, most engineering professors had either worked in industry or consulted extensively, and the facts and methods that constituted the knowledge base of the engineering curriculum were by and large those that the students would need in their careers. The tasks most engineers were called upon to perform involved mostly routine and repetitive calculations. Engineering students developed and sharpened the requisite skills by working through numerous laboratory exercises and industry-designed case studies and by participating in cooperative industrial work-study

The circumstances facing practicing engineers today are considerably different from those of the past, and the circumstances of the future will be even more different. Significant changes in engineering education will be required if we are to meet the needs of our graduates in preparing them for the challenges of the coming century.

programs and practice schools. The primary values of engineering practice at the time were functionality and profit. A good process was one that did what it was supposed to do in as profitable a manner as possible. Both the engineering curriculum and the faculty reinforced these values.

The circumstances facing practicing engineers today are considerably different from those of the past, and the circumstances of the future will be even more different. Significant changes in engineering education will be required if we are to meet the needs of our graduates in preparing them for the challenges of the coming century. Let us consider in somewhat greater detail the knowledge, skills, and values that will be necessary for engineers to deal successfully with the challenges raised in the previous section.

◀ *Knowledge* ▶

The volume of information that engineers are collectively called upon to know is increasing far more rapidly than the ability of engineering curricula to "cover it." Until the early 1980s, for example, most chemical engineering graduates went to work in the chemical or petroleum industry. Now they are increasingly finding employment in such nontraditional (in chemical engineering) fields as biotechnology, computer engineering, environmental science, health and safety engineering, semiconductor fabrication technology, and business and finance. To be effective across this broad spectrum of employment possibilities, our graduates should understand concepts in biology, physics, toxicology, fiscal policy, and computer and software engineering that are well beyond the range of the traditional chemical engineering curriculum. Many who work in companies that have international markets will also need to be conversant with foreign languages, which have been phased out of both undergraduate and graduate engineering curricula in recent decades. At the same time, the work done by any one engineer tends to occupy a relatively narrow band in the total spectrum of engineering knowledge. Unlike their counterparts of several decades ago, today's engineering students may never be called upon to work with basic elements of the traditional curriculum such as phase equilibria, thermodynamics, separations, reactions, and process design.

For these reasons, structuring a four-year, or even a five-year, engineering curriculum that meets the needs of most engineering students appears to be an increasingly elusive goal. One solution is to abandon the traditional one-size-fits-all curriculum model and instead to institute multiple tracks for different areas of specialization, relegating some traditionally required courses to the elective category.[13] Designing such tracks and keeping them relevant is a challenging task, but it can be and is being done at many institutions.

No matter how many parallel tracks and elective courses are offered, however, it will never be possible to teach engineering students everything they will be required to know when they go to work. A better solution may be to shift our emphasis away from providing training in an ever-increasing number of specialty areas to providing a core set of science and engineering fundamentals,[14] helping students integrate knowledge across courses and disciplines,[15] and equipping them with lifelong learning skills.[16,17] In other words, the focus in engineering education must shift away from the simple presentation of knowledge and toward the integration of knowledge and the development of critical skills needed to make appropriate use of it.

◀ *Skills* ▶

The skills required to address the challenges to future engineers raised in the first section may be divided into seven categories: (1) independent, interdependent, and lifelong learning skills; (2) problem solving, critical thinking, and creative thinking skills; (3) interpersonal and teamwork skills; (4) communication skills; (5) self-assessment skills; (6) integrative and global thinking skills, and (7) change management skills. From another perspective, ABET Engineering Criteria 2000 requires that future graduates of accredited programs should possess

(a) an ability to apply knowledge of mathematics, science, and engineering

(b) an ability to design and conduct experiments, as well as analyze and interpret data

(c) an ability to design a system, component, or process to meet desired needs

(d) an ability to function on multidisciplinary teams

(e) an ability to identify, formulate, and solve engineering problems

(f) an understanding of professional and ethical responsibility

(g) an ability to communicate effectively

(h) the broad education necessary to understand the impact of engineering solutions in a global/societal context

(i) a recognition of the need for and an ability to engage in lifelong learning

(j) a knowledge of contemporary issues

(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.[9,18]

In the following paragraphs we will suggest the parallels between our proposed classification of skills and the ABET criteria.

Independent Learning, Interdependent Learning, and Lifelong Learning Skills

(EC 2000 Outcomes a, d, e, and i)

Most students enter college as *dependent learners,* relying on their instructors to present, organize, and interpret knowledge. A model developed by Perry[19] describes the shift many students undergo from being dependent learners to independent learners to interdependent learners. Perry's model includes nine levels, of which levels 2 to 5 characterize most college students.[19-21]

. . . the focus in engineering education must shift away from the simple presentation of knowledge and toward the integration of knowledge and the development of critical skills needed to make appropriate use of it.

In Perry's model, dependent learners tend to be *dualists* (Level 2). In the dualist picture of the world, every point of view is either right or wrong, all knowledge is known and obtainable from teachers and texts, and the students' tasks are to absorb what they are told and then demonstrate having done so by repeating it back. A significant part of our responsibility as instructors is to move students from the dependent stance to being *independent learners,* who realize that all knowledge is not known and different points of view may come in shades of gray rather than being either black or white, and that their task is to acquire knowledge from a variety of sources and subject it to their own critical evaluation. Students at this level (which roughly corresponds to Level 4 of Perry's model) should be able to identify the pertinent factors and issues that affect a given situation, see the situation from a variety of perspectives, recognize what they need to know to resolve the situation, acquire the pertinent knowledge they do not already possess, and apply their knowledge to achieve a successful resolution. They should further be able to elaborate their knowledge so that future recall and application will be easy. Evidence suggests that some, but by no means all, students attain this level of development by the time they graduate.[21-23]

But the instructor's job does not end at this point. Students should be helped to go beyond *in*dependent learning to *inter*dependent learning, recognizing that all knowledge and attitudes must be viewed in context; that getting information from a variety of sources is more likely to lead to success than relying on a narrow range of sources and viewpoints, and that the peer group can be a powerful learning resource. These attitudes are characteristic of Level 5 on the Perry scale. Students routinely work with peers to identify key resources and to step through the superabundance of available information to identify what is really important, formulate learning objectives and criteria, assess the extent to which they can believe what they read, and learn from and communicate newly acquired information to others. In working with others, the students learn to recognize their own learning styles, strengths, and weaknesses, and to take advantage of the synergy that comes from people with a diversity of backgrounds and abilities working together toward a common goal.[24]

When students leave the university and enter the work world, they can no longer count on teachers, textbooks, and lectures to tell them what they need to know to solve the problems they are called upon to solve. The only resources they have access to are themselves and their colleagues. If we help them to become independent learners, developing and relying on their own reasoning ability rather than accepting information presented by others at face value, and interdependent learners, using the strength of the group to compensate for and overcome their own limitations, we will be equipping them with the lifelong learning skills they will need for success throughout their postgraduate careers.

Problem Solving, Critical Thinking, and Creativity

(EC 2000 Outcomes a, b, c, e, and k)

Some authors[25,26] identify critical and creative thinking as core skills that are applied to problem solving, while others[23,27-32] define problem solving as the primary skill, with critical and creative thinking as components. Norman[33] questions whether "general" problem-solving skills exist without subject context. Be all of that as it may, to be considered effective problem solvers, our students should be able to draw upon a wide range of analytical, synthetic, and evaluative thinking tools, problem-solving heuristics, and decision-making approaches. When given a problem to solve, they should be equipped to identify the goal and put it in context; formulate a systematic plan of attack that incorporates a suitable blend of analysis, synthesis, evaluation, and problem-solving heuristics; locate sources of information; identify main ideas, underlying assumptions, and logical fallacies, and evaluate the credibility of the identified sources; create numerous options, and classify and prioritize them; make appropriate observations and draw sound inferences from them; formulate and implement appropriate measurable criteria for making judgments; develop cogent arguments in support of the validity or plausibility of a hypothesis or thesis; generate new questions or experiments to resolve uncertainties; and monitor their solution process continuously and revise it if necessary.[22,26,34]

Interpersonal/Group/Team Skills
(EC 2000 Outcomes d, g, and f)

The image of the isolated engineer, working in solitary splendor on the design of a bridge or amplifier or distillation column, probably never was realistic. Engineering is by its nature a cooperative enterprise, done by teams of people with different backgrounds, abilities, and responsibilities. The skills associated with successful teamwork—listening, understanding others' viewpoints, leading without dominating, delegating and accepting responsibility, and dealing with the interpersonal conflicts that inevitably arise—may be more vital to the success of a project than technical expertise. Being aware of others' needs and taking them into consideration when making decisions—the essence of teamwork—is surely a prerequisite to functioning professionally and ethically, regardless of how these terms are interpreted, and is consequently a necessary condition for the fulfillment of EC 2000 Outcome f.

Communication Skills
(EC 2000 Outcomes d, g, and h)

The teamwork necessary to confront the technological and social challenges facing tomorrow's engineers will require communication skills that cross disciplines, cultures, and languages. Engineers will have to communicate clearly and persuasively in both speaking and writing with other engineers and scientists, systems analysts, accountants, and managers with and without technical training, within their company and affiliated with multinational parent, subsidiary, and client companies, with regulatory agency personnel, and with the general public. Like all the other skills mentioned, effective communication is a skill that can be taught, but doing so requires a conscious effort from those who design curricula.

Assessment and Self-Assessment Skills
(EC 2000 Outcomes d, f, and i)

Gibbs[35] suggests that "whoever owns the assessment, owns the learning." The more we can empower students to assess accurately the knowledge and skills of others

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and their own knowledge and skills, the more effective and confident they will become as learners. Moreover, as professionals all of our graduates will receive performance reviews and many will administer them to others. Developing assessment skills could be an important component of their preparation for professional practice.

Integration of Disciplinary Knowledge
(EC 2000 Outcomes a-e and h-k)

Chemical engineering students get used to solving problems within the narrow context of individual courses. They solve thermodynamics problems in the thermodynamics course and heat transfer problems in the heat transfer course, often never recognizing that the two subject areas are intimately related. As professionals, on the other hand, chemical engineers rarely solve "thermodynamics problems" or "heat transfer problems." Rather, they solve problems, drawing on knowledge from thermodynamics and heat transfer and economics and safety engineering and environmental science and any other discipline that pertains. Doing this well requires both generic problem-solving skills and integrated and structured knowledge of the engineering curriculum.[14,36] Thermodynamics and heat transfer should be seen as related applications of the law of conservation of energy and not as separate, self-contained subjects taught at different times by different instructors using different textbooks.

Managing Change
(EC 2000 Outcomes d, f, h, j, and k)

The one certainty about engineering in the coming decades is that it will change, because everything else will change. The growth of technology will lead to rapid product obsolescence and a decreasing need for engineers to perform the tasks that occupied most of them for most of this century, and also to a growth in nontraditional job markets for engineers, especially in the international arena. Industries that lack the capacity to adapt and change to shifting markets and new technologies will not survive, and successful engineers will be those who can manage change, especially when change is thrust upon them.

Modern universities have, with few exceptions, become totally dependent on research funds to support most of their functions . . . This circumstance has dictated the establishment of research achievement as the primary criterion for advancement up the faculty ladder, and the potential for research achievement as the primary criterion for faculty hiring. . . . Individuals . . . tend to put minimal effort into teaching so that they can concentrate on research, which they view (generally correctly) as the key to their career success.

◀ *Attitudes and Values* ▶

Vesilind[37] says that the most lasting effect of education on students is the maturation of their values and ethical sense. Essays on this subject[38-44] suggest that engineers should be inculcated with the values of willingness to cooperate, concern for the preservation of the environment, coequal commitment to quality and productivity, and involvement in service to others.

The fallacious assumption of those who designed the engineering curricula of the past half-century seems to have been that including several humanities courses should be sufficient to produce responsible and ethical engineers. The failure of the engineering curriculum to address attitudes and values systematically has had unfortunate consequences. Engineers often make decisions without feeling a need to take into account any of the social, ethical, and moral consequences of those decisions, believing that those considerations are in someone else's purview. By default, the decisions have consequently become the exclusive province of economists and politicians, who lack the ability to predict or evaluate their consequences.

The social penalties discussed in the introductory section have been the results of this development. EC 2000 Outcomes *f* (an understanding of professional and ethical responsibility), *h* (the broad education necessary to understand the impact of engineering solutions in a global/societal context), and *j* (a knowledge of contemporary issues), and in part, *i* (a recognition of the need for lifelong learning), arose from a perceived need to correct the situation.

OBSTACLES TO CHANGE

In the traditional approach to teaching, the professor lectures and assigns readings and well-defined convergent single-discipline problems, and the students listen, take notes, and solve problems individually. Alternative pedagogical techniques have repeatedly been shown to be more effective and much more likely to achieve the objectives set forth in the preceding section. Among those techniques are cooperative (team-based) learning, inductive (discovery) learning, the assignment of open-ended questions, multidisciplinary problems and problem-formulation exercises, the routine use of in-class problem-solving, brainstorming, and troubleshooting exercises, and other methods designed to address the spectrum of learning styles to be found among students in every class.[45-47]

The superiority of the alternative methods at achieving desired cognitive and affective educational outcomes has been demonstrated in thousands of empirical research studies[24,45-49] and is heavily supported by modern cognitive science.[50] Nevertheless, straight lecturing and convergent problems continue to predominate in engineering courses at most institutions. A substantial number of engineering professors are still unaware of alternative educational methods, and many who are aware of them choose not to incorporate them into their approach to teaching. There are several likely reasons for this inertia, aside from the inevitable human resistance to change.

Modern universities have, with few exceptions, become totally dependent on research funds to support most of their functions, including educational and administrative functions only marginally related to research. This circumstance has dictated the establishment of research achievement as the primary criterion for advancement up the faculty ladder, and the potential for research achievement as the primary criterion for faculty hiring. In consequence, many young faculty members either have little interest in doing high-quality teaching or would like to do it but feel that they cannot afford to invest the necessary time. Individuals in both categories tend to put minimal effort into teaching so that they can concentrate on research, which they view (generally correctly) as the key to their career success. Moreover, most professors begin teaching without so much as five minutes of training on how to do it. Even those who are genuinely concerned about their students and would like to be effective teachers automatically fall back on straight lecturing, which is the only instructional strategy most of them have ever seen.

Another obstacle to change is the fear of loss of control. Lecture classes in which student involvement is essentially limited to passive observation (perhaps broken by occasional questioning) and out-of-class problem solving is safe: the professor is in almost complete control of what happens in class. On the other hand, it is hard to predict what might happen in a student-centered class. Digressions may occur, making it difficult to stay with the syllabus, and the discussion may wander into areas where the professor is not all that comfortable. Perhaps worst of all, the students simply may not buy into the program, remaining indifferent, uncooperative, or perhaps hostile in their refusal to get involved in the planned activities.[51,52] Like any other skill, directing student-centered classes is an ability that can be learned and improves with practice. Unless some training is provided and feedback given on initial efforts, however, professors courageous enough to try the new teaching methods are likely to become discouraged, give up, and revert to straight lecturing.

In short, no matter how effective they may be, the new approaches to teaching will not automatically replace the old approach. The university administration must take steps to establish a suitable climate for change before any significant change can take place.

FACTORS SUPPORTING CHANGE

As imposing as the obstacles to change may be, we do not believe they are insuperable, and indeed several things are happening that are conducive to change.[1] As noted at the beginning of this article, legislatures and industry have been exerting increasing pressure on universities to pay more attention to the quality of their undergraduate teaching programs, and growing competition for a shrinking pool of applicants for engineering school has provided further impetus for change.

In the United States, the new ABET criteria were developed in response to these stimuli, and the knowledge that in a short time they will be used to evaluate all engineering programs is substantially increasing the pressure to change. Moreover, major support for educational reform has come from the National Science Foundation Division of Undergraduate Education and the NSF-sponsored Engineering Education Coalitions. This support has led to the emergence of a large and rapidly growing number of innovative programs and instructional methods and materials in the past decade, as a perusal of recent issues of the *Journal of Engineering Education* makes abundantly clear.

Finally, since both the National Science Foundation and ABET insist on accountability, both traditional and innovative instruction are being subjected to serious assessment and evaluation. The presence of hard evidence to support claims of improvement in learning should make it easier to disseminate educational reforms to the skeptical mainstream engineering professoriate.

THE CRITICAL QUESTIONS

The changes that will move engineering education in the desired directions may be grouped into four categories: (1) revisions in engineering curriculum and course structures; (2) implementation of alternative teaching methods and assessment of their effectiveness; (3) establishment of instructional development programs for faculty members and graduate students; and (4) adoption of measures to raise the status of teaching in society and in institutional hiring, advancement, and reward policies. In the next paragraphs, we will propose questions that should be addressed in each of these categories. The remaining papers in this series will be devoted to suggesting answers.

Engineering Curricula and Courses

- *What is the appropriate balance between "fundamentals" and "applications"? Should individual courses stress one of these or the other, or should the two be integrated within courses? Should the flow within a course or curriculum generally proceed from fundamentals to applications (deductive presentation, expository teaching) or from applications to fundamentals (inductive presentation, discovery learning, problem-based learning)?*
- *What steps can be taken to integrate class material across courses and disciplines, so that engineering students become accustomed to thinking along interdisciplinary lines in their approach to problem solving? How can "clusters of concepts" be presented systematically throughout the curriculum?*
- *How should the development of critical skills—those we outlined in this paper, and the overlapping set defined in ABET Engineering Criteria 2000—be facilitated in the curriculum? How much should be done within core engineering courses and how much should be relegated to specialized courses in such things as communication and ethics?*

Teaching Methods

- *What forms of in-class activities, homework assignments, laboratory exercises, and testing and grading policies and procedures, have been found most effective at increasing knowledge and critical skills and at promoting and reinforcing positive professional attitudes?*
- *What is an appropriate balance between teacher-centered and student-centered instruction? Between cooperative and individual learning? Between active experimentation and reflective observation? Between abstract concepts and concrete information? Between routine drill and high-level thinking problems, and between convergent (closed-ended) and divergent (open-ended) problems? How can these balances be achieved in practice?*
- *How can students be motivated to be self-directed*

learners? How can they be helped to overcome the resistance many of them feel to approaches that make them take more responsibility for their own learning?

- *How might we overcome faculty reluctance to try something new in the classroom?*

Instructional Development

- *What material should instructional development ("teacher training") programs cover? How much should be generic, and how much should be specific to engineering?*
- *Should the programs be mandatory or optional for faculty members? For graduate teaching assistants? For all PhD candidates?*
- *What do instructional development programs cost? How can they be financed?*
- *How do the different types of programs (seminars, workshops, courses) compare in effectiveness at improving teaching? In cost effectiveness?*

Faculty Hiring, Advancement, and Rewards

- *Does the requirement that every engineering professor be a disciplinary researcher to enjoy full departmental citizenship have a logical basis? Does it improve a university's teaching program? Its research program?*
- *Who will teach engineering practice in the coming years as the number of engineering professors with industrial experience continues to shrink? Who will write undergraduate textbooks? Advise undergraduates? Teach design? Keep the undergraduate laboratory running and periodically modernize it? Can adjunct professors fill these roles? Should they?*
- *Who will develop innovative and effective teaching methods in the future, do the research to validate them, and help other faculty members implement them?*
- *Is it possible to assure that every engineering department has at least a few individuals who can perform the preceding tasks with dedication and skill? Can engineering education survive without such individuals? What incentives, rewards, and policies will be required to hire and keep them on our faculties? Can their presence be maintained without completely overturning the current financial structure of the university, which depends so heavily on research funding?*

IF YOU GET ONLY ONE IDEA FROM THIS PAPER

We have described many concerns and trends in this paper. The key idea is that traditional instructional methods will probably not be adequate to equip engineering graduates with the knowledge, skills, and attitudes they will need to meet the demands likely to be placed on them in the coming decades, while alternative methods that have been extensively tested offer good prospects of doing so.

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THE FUTURE OF ENGINEERING EDUCATION

Part 2. Teaching Methods that Work

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Deficiencies in engineering education have been exhaustively enumerated in recent years. Engineering schools and professors have been told by countless panels and blue-ribbon commissions and, in the United States, by the Accreditation Board for Engineering and Technology that we must strengthen our coverage of fundamentals; teach more about "real-world" engineering design and operations, including quality management; cover more material in frontier areas of engineering; offer more and better instruction in both oral and written communication skills and teamwork skills; provide training in critical and creative thinking skills and problem-solving methods; produce graduates who are conversant with engineering ethics and the connections between technology and society; *and* reduce the number of hours in the engineering curriculum so that the average student can complete it in four years.[1]

. . . even if nothing new is added to the existing curriculum, confining it to four years will be almost impossible unless more efficient and effective ways to cover the material can be found. . . . The reality is that better teaching methods exist.

This is an impressive wish list—especially when the last item is included—that cannot possibly be fulfilled using the approach to educating engineers that has predominated in the past fifty years. If, for example, courses continue to be confined to single subjects (heat transfer in one course, thermodynamics in another, environmental engineering in another, technical writing in another, etc.), it will take a six- or seven-year curriculum to produce engineers who have the desired proficiency in the fundamentals and are conversant with methods of modern engineering practice, culturally literate, and skilled in communication. Moreover, if students are assigned only well-defined convergent problems, they will never gain the skills needed to tackle and solve challenging multidisciplinary problems that call for critical judgment and creativity. Finally, even if nothing new is added to the existing curriculum, confining it to four years will be almost impossible unless more efficient and effective ways to cover the material can be found.

The reality is that better teaching methods exist. The literature in general education, technical education, and educational psychology is replete with methods that have been shown to facilitate learning more effectively than the traditional single-discipline lecturing approach. Unfortunately, these developments have so far had relatively little impact on mainstream engineering education. Although their content has changed in some ways and the students use calculators and computers instead of slide rules, many engineering classes are taught in exactly the same way that engineering classes in 1960 were taught.

The purpose of this paper is to offer alternatives. The instructional methods to be described have been chosen to meet the following criteria:

- *They are relevant to engineering education.*

  Many innovative instructional methods have been developed for nontechnical courses and emphasize free discussion and expressions of student opinions, with minimal teacher-centered presentation of information. We believe that involvement of students is critical for effective classroom learning; however, much of the basic content of engineering courses is not a matter of opinion. Educational approaches that emphasize process exclusively to the detriment of content will not be considered.

- *They can be implemented within the context of the* *ordinary engineering classroom.*

An instructional approach based entirely on, say, self-paced computer-assisted instruction might be extremely effective—at least for some students—but it might also require a specialized network of workstations that could cost an institution several million dollars to purchase and set up. Such programs will be left off the list. The techniques we describe can be implemented in regular classrooms and laboratories with no tools or devices beyond those routinely available to all engineering instructors.

- *Most engineering professors should feel reasonably comfortable with them after a little practice.*

  It is conceivable, for example, that getting students to role-play molecules in a reactive gas would teach them more about the dynamic behavior of a given system than would a standard lecture. Some instructors find methods like this useful and can manage to pull them off; still, it is safe to say that most engineering professors would never contemplate doing anything like that in their classes. Such methods will not be included in our list of recommendations.

- *They are consistent with modern theories of learning and have been tried and found effective by many educators.*

  The literature is full of articles by professors who have tried new methods and written about the results. But the validity of a method must remain suspect if the only evidence on its behalf is one person's testimony that "I tried this and liked it and so did the students." The methods to be given are consistent with results of theoretical and/or empirical studies in the cognitive and educational psychology literature, and they have each been implemented successively in engineering classes by independent investigators.

This paper surveys some (but by no means all) instructional methods that meet these criteria. Several excellent references describe other techniques and summarize the supporting research.[2-4]

FORMULATE AND PUBLISH CLEAR INSTRUCTIONAL OBJECTIVES[5-10]

Instructional objectives are statements of what students should be able to do to demonstrate their mastery of course material and desired skills. They contain a stem specifying the point at which the mastery should occur, followed by one or more phrases describing the expected behavior, with each phrase beginning with an action verb. For example

> *When this chapter has been competed, the student should be able to* define *the variables in the ideal gas equation of state in terms a high school senior could understand,* calculate *the value of any one of the variables from given values of the other three,* estimate *the error in the calculated values, and* outline *the derivation of the ideal gas equation from the kinetic theory of gases.*

The common stem of the four objectives in this paragraph is "When this chapter has been completed." An alternative stem might be "In order to do well on the next test." The phrases that define the objectives begin with the verbs *define, calculate, estimate, and outline.* Other acceptable verbs include *list, identify, explain (without using jargon), predict, model, derive, compare and contrast, design, create, select, optimize,* and many others.

The behavior specified in an instructional objective must be directly observable by the instructor and should be as specific and unambiguous as possible. For this reason, verbs such as *know, learn, understand,* and *appreciate* are unacceptable. These are critically important goals, but they are not directly observable. For example, if an instructor states that her goal is for her students to understand the first law of thermodynamics, she might be asked how she will know whether or not they do. She would then list the things she would ask them to do to demonstrate their understanding. The items on the list would constitute the instructional objectives associated with the specified goal. If there could be any possible doubt about whether or not an objective has been met, metrics should be included in the defining statement.

Instructional objectives may involve skills that cover a broad spectrum of complexity and difficulty. The book *Taxonomy of Educational Objectives (Cognitive Domain)* developed by Bloom and colleagues[10] defines a hierarchy of six levels:

1. *Knowledge*—repeating memorized information
2. *Comprehension*—paraphrasing text; explaining concepts in jargon-free terms
3. *Application*—applying course material to solve straightforward problems
4. *Analysis*—solving complex problems; developing process models and simulations; troubleshooting equipment and system problems
5. *Synthesis*—designing experiments, devices, processes, and products
6. *Evaluation*—choosing from among alternatives and justifying the choice; optimizing processes; making judgments about the environmental impact of engineering decisions; resolving ethical dilemmas

Levels 1 through 3 are commonly known as "lower-level skills" and Levels 4 through 6 are "higher-level skills." Most undergraduate engineering courses focus on Level-3 skills: an analysis of one four-year engineering program showed that 2345 out of 2952 problems assigned (79%) were Level 3 or lower.[11] On the other hand, probable demands on engineering graduates in the coming decades and many of the new ABET accreditation criteria (Engineering Criteria 2000) involve skills at Levels 4 through 6.[1]

Recommendation

Write instructional objectives for a course (or a section of a course) that encompass both knowledge of content and mastery of the skills you wish the students to develop. At all levels of the engineering curriculum—including the first year—include some higher-level problem-solving skills (*e.g.,* multidisciplinary analysis, design, critical thinking) and the "soft" skills (*e.g.,* oral and written communication, teamwork, social and ethical awareness) specified in EC 2000. Make the objectives as detailed and specific as possible; rather than simply saying that the student should be able to "design a chemical plant," list all the different things the student will be expected to do (look up, estimate, calculate, create, analyze, select, explain) when designing the plant. Make class exercises, homework assignments, and tests consistent with the objectives. Give the objectives to the students to use as study guides.

Justification

Once formulated, instructional objectives reveal which course topics are most important and deserve the greatest coverage, and which involve little else than memorization and thus merit only cursory attention or possible elimination from the curriculum. Objectives enable instructors to design consistent homework assignments that provide practice in all of the desired skills and tests that assess mastery of the skills. They make ideal study guides for the students; the more explicit you are about what you want the students to be able to do, the more likely they will be to succeed at doing it.[12] The objectives provide an excellent outline of the course content, for instructors teaching the course for the first time as well as instructors of subsequent courses. Finally, the instructional objectives for all departmental courses collectively reveal gaps and redundancies in the curriculum and provide an excellent curriculum overview to accreditation visitors, especially if homework assignments and tests closely follow the objectives.

ESTABLISH RELEVANCE OF COURSE MATERIAL AND TEACH INDUCTIVELY

Instructors often start a course by presenting totally new material without putting it in any context. They make no attempt to relate the material to things students already know about from their own experience or from prior courses, nor do they preview how it will be needed to solve problems of

Once formulated, instructional objectives reveal course topics that are most important and deserve the greatest coverage, and which ones involve little else than memorization and thus merit only cursory attention or possible elimination from the curriculum.

the types the students will encounter later in the curriculum or in professional practice. These instructors are pursuing what might be called the "Trust Me" approach to education (as in "Trust me—what I'm teaching you may seem pointless now, but in another year, or perhaps in four years, you'll see why you needed it.").

Recommendation

Begin teaching each course and each new topic within it by describing the physical and chemical phenomena to be studied and the types of problems to be solved, using examples familiar to the students if possible. Discuss several realistic situations in which engineers and scientists are required to understand the phenomena and solve the problems. A good way to begin is to divide the class into groups of three or four and have the groups generate as many examples as they can think of in a brief period of time, adding your own to supplement whatever they come up with. For example

> *For the next two weeks, we're going to be discussing characteristics of a fluid flowing through a pipe. In groups of three, come up with as many situations as you can that involve this subject—three people talking, one writing down the ideas. You have one minute—go!*

Give them the allotted time (or a little more if they seem to need it), then stop them and collect the ideas, listing them without criticism. At least some of the groups are almost certain to come up with home plumbing, irrigation, oil and coolant flows in engines, municipal water and sewer flows, flow of body fluids, and a variety of industrial examples. Supplement their list with your own. You might then continue

> *Ok, you're now engineers designing a piping system to move fluid from a storage tank to a reactor at a specified rate. What will you need to know or figure out? Same groups, two minutes—go!*

It may occur to some of the groups that they will need to know the density and viscosity of the fluid, the distance from the tank to the reactor, whether the fluid is corrosive or dangerous in some way, the pipe material (aluminum, copper, stainless steel, plastic), and costs of piping, pumps, and power, and they will have to determine the pipe diameter, the required valves, fittings, and flow meters, the kind of pump to use, the size of the pump, and the path of the system. Give hints if necessary, and add items to their list. Spending ten minutes on such an exercise at the beginning of a new topic can go a long way toward motivating the students to pay attention to what takes place in the subsequent two or three weeks.

The flow of information in the presentation of course material should generally follow that of the scientific method: begin with induction, proceeding by inference from specifics (facts, observations, data) to generalities (rules, theories, correlations, mathematical models), and then switch to deduction, using the rules and models to generate additional specifics (consequences, applications, predictions).

Justification

Our goal in teaching is to get information and skills encoded in our students' long-term memories. Cognitive research tells us that we learn new material contextually, fitting it into existing cognitive structures,[13-15] and new information that cannot be linked to existing knowledge is not likely to be retained. Moreover, once information is stored in long-term memory, cues are required for us to recall and use it. Linking the new material to familiar material provides a natural set of cues.

The motivational and learning benefits of providing context, establishing relevance, and teaching inductively are supported throughout the literature on cognitive and educational psychology and effective pedagogy.[15,16] Ramsden and Entwistle[12] note the motivational effectiveness of "vocational relevance," and the same authors show that establishing relevance is one of the factors that induces students to adopt a "deep" (as opposed to superficial) approach to learning.[12,17]

The problem with introducing abstraction [is that it is] not firmly grounded in the student's knowledge and experience . . . the new material is not linked to existing cognitive structures and so is unlikely to be transferred to long-term memory.

Inductive teaching (wherein the information flow generally proceeds from specifics to generalities) takes several forms in the literature, variously known as discovery learning, inquiry learning, problem-based learning, just-in-time learning, and the case-study method. Problem-based learning (PBL), which involves students working in teams on projects built around realistic problems, has been extensively discussed and shown to be effective in science, engineering, and medicine.[18-23] (This approach will be treated in greater detail in the next paper in this series.)

The literature on learning styles also supports the recommendations in this section.[24-33] Kolb[27-29] suggests "teaching around the cycle," starting with a concrete experience, documenting observations, creating an abstract model, and then experimenting and testing the model. This cycle has been used to design a college-wide instructional program in engineering.[30-31] Establishing the relevance of new material before going into the details can provide the concrete experience that starts the learning cycle.

BALANCE CONCRETE AND ABSTRACT INFORMATION IN EVERY COURSE

Material in engineering courses may be categorized as being *concrete* (facts, observations, experimental data, applications) or *abstract* (concepts, theories, mathematical formulas, and models). Most engineering courses contain material in each category, but the balance varies considerably from one course to another and from one instructor to another in a given course.

In recent decades, the balance between the two categories in the engineering curriculum has been shifting toward abstraction. The old courses on industrial processes and machinery have been largely replaced with courses that emphasize mathematical expressions of fundamental scientific principles. While this movement may have initially had the effect of correcting an imbalance, it has proceeded to an extent that has negative consequences for many students. The problem with introducing abstraction that is not firmly grounded in the student's knowledge and experience has been described in the preceding section; the new material is not linked to existing cognitive structures and so is unlikely to be transferred to long-term memory.

Recommendations

Balance concrete and abstract content in the presentation of all engineering courses. Most courses currently contain a reasonable level of abstraction, so the challenge is generally to provide sufficient concrete material for those who need it. Some suggestions for doing so follow:

- Do everything listed under the category of establishing relevance in the preceding section.
- Intersperse concrete illustrations and applications throughout theoretical developments rather than waiting until the final formulas have been derived. When possible, tie the examples back to the "real-world" systems and situations introduced in the motivating introduction to the subject.
- When illustrating how formulas and algorithms are applied, use numbers rather than algebraic variables in at least the first example. The greater the level of generality of the theory, the greater the need for specificity in the examples. Some students—specifically, sensing learners—understand "5" at a level that they may never understand "x".[25,32,33]
- Provide visual illustrations and demonstrations of course-related material when possible. Most students get a great deal

more out of visual information than verbal information (written and spoken words and mathematical formulas).[25] Show pictures, sketches, schematics, plots and flow charts, and computer simulations of process equipment and systems. Take the class to the local boiler house and point out pumps, flowmeters, boilers, heat exchangers, refrigeration units, and turbines. Bring demonstrations into class, such as those described by Wood[34] for heat transfer and Kresta[35] for fluid mechanics.

- Never venture too far from the realm of experimentation. In abstract subjects such as thermodynamics and process control, for example, it is easy for the students to drown in an alphabet soup of variables that bear no apparent relationship to anything one can measure in a laboratory or plant (*e.g.,* entropy, free energy, and transfer functions). It is important to remember that the ultimate goal of all theories is to correlate data from measurements on physical systems and to predict the outcomes of future measurements. As each abstract variable is introduced, provide examples of how it could be determined experimentally and how values of measured variables can be predicted from known values of the abstract variables, and give such problems as homework assignments. Once the students have manipulated a given variable or function in a variety of contexts, its meaning can be assumed to be anchored in memory, but in the absence of such examples and exercises no such assumption can be made.

Just as overemphasizing mathematical formulations of course principles works against the sensing learner, overemphasizing facts and computational algorithms and shortchanging conceptual understanding works against intuitive learners.[33] (This concrete/abstract imbalance is also not in the sensors' best interests, but it is less likely to make them uncomfortable.) Engineering students are not generally overloaded with spare time. If they can get away with memorizing problem solutions without understanding or questioning the underlying concepts and methods, many will do it.[17]

One way to help students gain a deeper understanding of course material is to ask questions that require such an understanding, first in class problems and homework and then on tests. For example,

- Equation (8-34) in the textbook is presented with only a sketchy explanation of where it comes from. Derive it, starting with Eq. (8-5).
- In Monday's handout there are a number of suggestions to "prove" or "verify" some statement or result. At least one of them will show up on the next test. I won't go over them unless asked. (Or, I'll go over them during my office hours, but only if you demonstrate that you've attempted them yourself.)
- Explain what a vapor pressure is in terms a high school senior could understand.
- Why do you feel comfortable in 20°C air and freezing in 20°C water? Your explanation should involve several concepts introduced in this course.
- Make up and solve a problem related to the material just covered.[36,37] The problem must be original, but you can get ideas and help from one another and from me. *Start simply the first time you do this in class, and gradually build in more depth. For example,*
    - Make up but don't solve a problem involving Raoult's law.
    - Make up and solve a problem involving Raoult's law.
    - Make up and solve a problem involving Raoult's law. If your problem is straightforward (given this, calculate that) and there are no mistakes, you'll get a "C"; to earn full credit the problem should involve a realistic situation.
    - Make up and solve a problem that involves both Raoult's law and what you covered during the last two weeks of your organic chemistry course.

Provide visual illustrations and demonstrations of course-related material when possible. Most students get a great deal more out of visual information than verbal information (written and spoken words and mathematical formulas). Show pictures, sketches, schematics, plots and flow charts, and computer simulations of process equipment and systems.

You may not get many good problems the first time or two you do exercises like these, but if you provide feedback and give examples of successful efforts, many students will surprise you (and themselves), both with the quality of their problems and by how thoroughly they learned the material in the course of the exercise.[36,37]

As noted in the previous section, a good way to achieve concrete/abstract balance is to "teach around the cycle."[26-31] When presenting a new concept, start with a physical demonstration or real-world example, model the results, test the model through active experimentation, and explore its implications. You might also find it worthwhile to have students measure their own learning styles and talk about the implications. The more they understand their own preferences, the more they can capitalize on the strengths of their preferred styles and work to build their capabilities in their less-preferred styles. Felder and Soloman's *Index of Learning Styles*[38] and Keirsey's *Temperament Sorter*[39] are accessible on-line and easy to use for this purpose.

Justification

Piaget[40] suggests that human capabilities evolve in stages, beginning with the *sensory-*

motor stage (up to age 2) and proceeding through *pre-operational* (ages 4 through 7) and *concrete operational* (about 7 to 12) stages to the *formal operational* stage. Concrete operational thinkers can think logically in terms of objects, but have difficulty replacing objects by symbols. They can acknowledge different viewpoints and cause-effect logic, but they have trouble generalizing through verbal or proportional reasoning. *Formal operational* thinkers can replace objects with symbols, generalize and work with abstract concepts, use verbal and proportional reasoning, and derive cause-effect relationships from results of experiments.

Piaget stated that the shift from concrete operational to formal operational thinking should occur by age 12; but more recent observations suggest that many first-year college students have not yet made it. Williams and Cavallo,[42] working with freshmen in physics courses, found that most of their subjects were concrete operational, incapable of grasping abstract concepts that were not firmly embedded in concrete experience. By including concrete examples in our teaching and explicitly showing how they can be generalized, we can help students make the shift from concrete to formal operational thinking.[43]

Learning-style differences also provide justification for establishing a good concrete/abstract balance in every engineering course.[24-26,32,33] Sensing learners tend to be practical and methodical; intuitors tend to be imaginative and quick-thinking. Sensors are more comfortable with concrete information (facts, data, "real-world" phenomena) than with abstractions (theories, concepts, and models), and the converse is true of intuitors. Both sensing and intuitive learners make excellent engineers, although they tend to gravitate to different specialties. Sensors make excellent experimentalists and production engineers; intuitors do well in design and theoretical research and development, and both types may become excellent managers and administrators. Industry and academia need individuals with both type preferences.

Most engineering undergraduates are sensors, while most engineering professors are intuitors.[44,45] Most intuitive professors, and even many of the sensing professors, teach in an intuitor-oriented manner, emphasizing theories, mathematical models, and abstract prose to students who respond best to concrete examples, well-established problem-solving procedures, and material that has a clear connection to the "real world" (a classic sensor's phrase). This mismatch has several unfortunate consequences for the sensing learners. Faced with an incessant barrage of material that seems remote and abstract, they have difficulty absorbing the material, become bored in class, tend to do poorly on tests (frequently running out of time on them) and tend to get lower grades in engineering courses than their intuitive counterparts, even though both types do equally well as practicing engineers.

Making courses overwhelmingly abstract is also a disservice to the intuitors. Even if they intend to go on to graduate school and research careers, they need to strengthen their sensing skills (observation of and attention to details, careful methodology, replication of measurements and calculations), and they will not do so if they are not challenged to do so in their courses.

PROMOTE ACTIVE LEARNING IN THE CLASSROOM

In the traditional approach to higher education, the professor dispenses wisdom in the classroom and the students passively absorb it. Research indicates that this mode of instruction can be effective for presenting large bodies of factual information that can be memorized and recalled in the short term. If the objective is to facilitate long-term retention of information, however, or to help the students develop or improve their problem-solving or thinking skills, or to stimulate their interest in a subject and motivate them to take a deeper approach to studying it, instruction that actively involves students has consistently been found more effective than straight lecturing.[2,3,46,47] The challenge is to involve most or all of the students in productive activities without sacrificing important course content or losing control of the class.

Recommendation

Several times during each lecture period, ask the students to form into groups of 2 to 4 and give them brief exercises that last anywhere from 30 seconds to 3 minutes. The exercises may involve answering questions of the type instructors routinely ask the class as a whole, or they may call for problem solving or brainstorming. For example,

- *Outline a strategy for solving the problem just posed.*
- *Draw a flowchart (schematic) for the process just described.*
- *Think of as many practical applications as you can of this (system, device, formula).*
- *Get started on the solution of the problem and see how far you can get with it in two minutes.*
- *What is the next step in the derivation?*
- *Complete this calculation.*
- *Prove or verify this result.*
- *Suppose you carry out experimental measurements and the results fail to agree with the theoretical formula we just derived. Think of as many possible explanations as you can.*
- *What questions do you have about this material?*

The groups should generally be given a short time to respond—long enough to think about the question and to begin to formulate an answer, but not necessarily to work out complete solutions.

Vary the format of these exercises to prevent their becoming as tedious and ineffective as straight lecturing. Assign some to pairs, some to groups of three or four, and some to individuals. Sometimes ask students to work on a problem individually, and then compare their answers with a partner ("think-pair-share"). Sometimes give a rapid succession of such exercises, and sometimes lecture for 10-15 minutes between exercises.

To maximize the likelihood that most or all of the students will be actively involved and that they will remain on task, call on several individuals or groups to give their responses when the allotted time has elapsed. If you only call for volunteers to share responses, the students will know that the answer will eventually be forthcoming and will have no incentive to participate in the activity—and many will not; but if they know that any one of them could be called on, fear of embarrassment will induce most of them to do the work so they will be ready with something if they are chosen.

Active learning methods make classes much more enjoyable for both students and instructors. Even highly gifted lecturers have trouble sustaining attention and interest throughout a 50-minute class. After 10-20 minutes in most classes, the students' attention starts to drift, and by the end of the class boredom is rampant. Even if the instructor asks questions in an effort to spark some interest, nothing much happens except silence and avoidance of eye contact. Tests of information retention support this picture of what happens in terms of recall: immediately after a full lecture, students were able to recall about 70% of the content presented in the first ten minutes but only 20% of the content of the last ten minutes.[2]

When active learning exercises are interspersed throughout a lecture, the picture changes. Once a class accustomed to group work gets started on a problem, the classroom atmosphere is transformed: discussions, arguments, and occasional laughter can be heard, all sounds of learning taking place. Even students who may not be doing much talking are engaged in thinking about the question at hand instead of just mechanically transcribing notes. Just five minutes of such activities in a 50-minute class can be enough to keep the students attentive for the remaining 45 minutes of lecturing. Many references offer specific suggestions for incorporating active learning exercises in the classroom.[46-50] Felder[51,52] and Woods[53] discuss the implementation of active learning in large classes, and Felder[51] discusses how to incorporate active learning without sacrificing content coverage.

Several authors have developed more formal active learning activities. One is "TAPPS" (thinking-aloud pair problem solving), an activity where pairs of students take turns working their way through a problem solution;[54] another is the "Osterman feedback lecture," where two 20-minute mini-lectures are separated by a ten-minute activity, the latter usually being a short problem that requires the students to have learned certain material before class;[18] and still another is "team learning," a more formal cooperative learning structure where student teams work on structured learning projects in every class session.[55] All of these techniques require more time and training to implement than the brief turn-to-your-neighbor exercises described previously, but the potential return in depth of learning is greater.

Justification

Literature supporting the notion that active, student-centered learning is superior to passive, teacher-centered instruction is encyclopedic.[13,14,46-48] People acquire knowledge and skills through practice and reflection, not by listening to others telling them how to do something. Straight lecturing may succeed at promoting short-term factual recall, but active approaches have consistently been shown to be superior for promoting long-term retention of information, comprehension, problem-solving skills, motivation to learn, and subsequent interest in the subject. Active learning is one of the seven, evidence-based recommendations for improving learning summarized by Chickering and Gamson,[56] and the active learning exercises described above also provide prompt feedback, another of the recommendations.

USE COOPERATIVE LEARNING

Cooperative learning (CL) is an instructional approach in which students work in teams on a learning task structured to have the following features:[48]

- *Positive independence.* There must be a clearly defined group goal (complete the problem set, write the lab report, design the process) that requires involvement of every team member to achieve. If anyone fails to do his or her part, everyone is penalized in some manner.
- *Individual accountability.* Each student in the team is held responsible for doing his or her share of the work and for understanding everyone else's contribution.
- *Face-to-face promotive interaction.* Although some of the group work may be parceled out and done individually, some must be done interactively, with team members providing one another with questions, feedback, and instruction.
- *Appropriate use of interpersonal and teamwork skills.* Students should be helped to develop leadership, communication, conflict-resolution, and time-management skills.
- *Regular self-assessment of team functioning.* Teams should periodically be required to examine what they are doing well together and what needs improvement.

Cooperative learning exercises may be performed in or out of class. Common tasks for CL groups in engineering are completing laboratory reports, design projects, and homework assignments in lecture courses. Only one problem set or report is handed in by a group, and one group grade is assigned to the project—but adjustments for individual team citizenship (or lack thereof) can and should be made. Pre-examination group study sessions can also be set up to meet out of class, with bonus points being awarded to members of groups for which the team average test grade exceeds a specified value.

Recommendation

The following suggestions are based on material in Johnson, Johnson, and Smith,[48] Felder and Brent,[57,58] and Millis and Cottell.[59]

- *Explain to students what you are doing and why.* As with in-class active learning methods, cooperative homework may not be welcomed enthusiastically by all students. Some regard it as a game the instructor is playing at their expense or an experiment with them as the guinea pigs, and some may complain that the instructor is not doing his or her job (which they see as lecturing to them on everything they will need to know for the tests). Felder and Brent[60] discuss the origin and forms of student resistance to active and cooperative learning and suggest strategies for defusing and eventually overcoming the resistance. On the first day, twenty minutes spent giving some of the reasons for using the approach (*e.g.,* it prepares students to function in the environment in which engineers work) and explaining the proven educational benefits to students (*e.g.,* higher grades and lower dropout rates) can go a long way toward overcoming the resistance. Another option is to run a mini-workshop on managing change.[18,19]

In a mixed-ability group, the weaker students gain from seeing how better students study and approach problems, and the stronger students usually gain deeper understanding of the subject through their attempts to explain the material, a phenomenon familiar to every professor.

- *Assign some or all homework to teams of 3-4 students.* In teams of two, one person tends to dominate and there is usually no good mechanism for resolving disputes, and in teams of five or more someone is usually left out of the process. Collect one assignment per group.
- *Form the groups yourself.* Considerable research shows that instructor-formed teams on average function better than self-selected teams. When students self-select groups, the top students often find one another and form groups, leaving the weak students to shift for themselves, which is unfair. Also, good friends find each other, leading to situations where their teammates are never fully integrated into the team. Particularly in the freshman and sophomore years, when most attrition from the curriculum occurs, under-represented minorities (including women) should not be isolated in teams. The ideal team is heterogeneous in ability (which we will say more about shortly), with team members who have common interests and common blocks of time when they can meet outside class. SAT or ACT scores or grades in prerequisite courses can be used as measures of ability, or a diagnostic test given early in the course can be used for the purpose of forming teams.
- *Form teams that are heterogeneous in ability level.* The members of a team of only weak students are obviously at a disadvantage (although sometimes they might do surprisingly well), and the members of a uniformly strong team may choose to divide up the homework and to communicate only cursorily with one another. Neither group receives the full benefits of cooperative learning. In a mixed-ability group, the weaker students gain from seeing how better students study and approach problems, and the stronger students usually gain deeper understanding of the subject through their attempts to explain the material, a phenomenon familiar to every professor.
- *Assign team roles that rotate with each assignment.* Three indispensable roles are the *manager* (organizes the assignment into subtasks, allocates responsibilities, and keeps the group on task), the *recorder* (writes the final report or problem solution set, or for large projects, assembles the report), and the *checker* (proofreads and corrects the final report before it is submitted). Other roles that may be performed separately or combined with one of the preceding roles include *group process monitor* (makes sure that every team member contributes and that all contributions are acknowledged by the others, verifies that every team member understands each part of the completed assignment) and the *skeptic* (plays the role of devil's advocate, suggests alternative possibilities, keeps the group from leaping to premature conclusions). Only the names of the students who actually participated should appear on the solution, with their team roles for that assignment identified. In a lecture course, the roles should rotate with each assignment so that a student cannot repeat as (say) manager until every other team member has held that position.
- *Promote positive interdependence.* Assign roles. Provide only one set of materials and require only one team product. Provide specialized training to individual team members on different aspects of the project that they must then bring back to the group effort (this technique is known as "jigsaw" in the cooperative learning literature). Give bonuses on tests to groups when the team average exceeds 80 (or some other specified value). Randomly select one member of each group to present a problem solution or report on a specific aspect of the project and give everyone in the group the grade earned by that individual. If you use the last strategy (which also promotes individual

accountability), tell the students well in advance that you plan on doing so, but do not provide much advance notice of which students will present on which parts of the assignment.

- *Get teams to assess how well they are functioning.* Periodically ask the students to spend five to ten minutes at the end of their work session assessing their performance, identifying their strengths, and setting goals for improvement.[19,62,63] A summary of the assessment might be included with the group problem solution or in individual journals on the group process.
- *Consider doing some testing of pairs or groups.* One mechanism is to administer and score an individual test and then to allow CL teams to retake the test (perhaps as a take-home exam) to earn additional points. The advantage of this procedure is that most students will achieve a deeper understanding of how to solve all the test problems; the disadvantage is that it requires more grading. Dekker and Stice[64] recommend giving tests to pairs of students as an alternative to individual tests and offer ideas for structuring such tests.
- *Do not re-form groups too often.* A team should remain together for at least a month in order to evolve through the "form, storm, norm, and perform" evolution of team development. If students know that they will only have to remain in a team for two or three weeks, they will have little incentive to confront and overcome the interpersonal problems that commonly arise in team development. If, however, they know they are going to be together for a longer period of time, they are forced to deal with the problems by establishing norms, developing strategies for coping creatively with conflict, and taking advantage of and valuing individual talents and learning styles.
- *Provide an escape mechanism for teams having severe difficulties.* Roughly halfway through the semester, announce that you will dissolve all of the teams and form new ones, except that a team may stay together if each member sends a note to the instructor expressing a desire to do so. Typically, all but the most highly dysfunctional teams elect to remain together, and the problem students in the groups that dissolve often change their behavior in their new groups. Consider instituting mechanisms for teams to fire uncooperative students and for individuals to quit uncooperative teams when all other avenues (including instructor intervention) have been exhausted and prior warnings have been given.[58]
- *Do not assign course grades on a curve.* If students recognize that by helping someone else they could be hurting themselves (as is the case when grades are curved), they may be inclined to avoid cooperation, making it less likely that the benefits of cooperative learning will be realized. On the other hand, if they are guaranteed a given grade if they meet a specified standard (for example, a weighted average grade of 88 or better for an A), they have every incentive to help their teammates.
- *Start small and build.* If you have never used cooperative learning and you are not working with a colleague who is experienced in this approach, you might consider beginning on a relatively small scale, with several assignments done by groups and the rest done individually. Once you gain confidence, increase the level of your involvement to a point that feels comfortable to you. When problems arise, remember to consult references on cooperative learning for ideas about how to deal with them.

Justification

Most engineering is done cooperatively, not individually, and technical skills are often less important than interpersonal skills in getting the job done. In survey after survey, representatives of industry place communication and teamwork at the top of their lists of desirable skills for new engineering graduates. If teamwork is such a critical part of what engineers do, surely engineering schools should provide some guidance in how to do it.

Cooperative learning may be the most thoroughly researched instructional method in all of education, and a vast and still rapidly growing body of research supports the effectiveness of the approach.[48,57,59,65-68] Studies have shown that compared to students taught traditionally (that is, primarily with lectures and individual homework), cooperatively taught students tend to have better and longer information retention, higher grades, more highly developed critical-thinking and problem-solving skills, more positive attitudes toward the subject and greater motivation to learn it, better interpersonal and communication skills, higher self-esteem, lower levels of anxiety about academics, and, if groups are truly heterogeneous, improved race and gender relations. Another benefit is that when homework is done cooperatively, there are three to four times fewer assignments to grade.

Felder, *et al.*,[58,68] report on a longitudinal study comparing the conventional instructor-centered approach with an alternative approach that combined all of the methods recommended in this paper. Students experiencing the alternative approach outperformed students experiencing the conventional approach in their academic performance, development of higher-level thinking skills, retention in chemical engineering, and attitudes toward their educational experience.

A variety of factors account for the observed benefits of cooperative learning. Weaker students working individually are likely to give up when they get stuck; working cooperatively with stronger students to assist them, they keep going to completion. Many strong students tend to do the minimal work required to complete the assignment, which may not require deep understanding of concepts; when faced with the task of explaining and clarifying material to weaker students, they often find gaps in their own understanding and fill them in. Students working alone may tend to delay completing assignments or skip them altogether; when they know others are counting on them, they are often driven to do the work on time.

GIVE CHALLENGING BUT FAIR TESTS

Although we might wish it were otherwise, for many of our students tests are the primary motivation to study. The students may attend every class and complete all the assignments, but it is their preparation for the tests that determines the breadth and depth of their learning. The burden is on the instructor to make the tests challenging enough to push each student to learn to the greatest extent of which he or she is capable.

But, just as tests can motivate students to learn at a deep level, they can also lead to student demoralization and hostility (both of which correlate with poor performance) if they are perceived by the students as being unfair. The two most common types of tests in this category are tests that are too long and tests that contain surprises—problems with twists unlike anything the students have seen before and problems that call for skills that were never taught in class or required on homework assignments.

Some students—sensing learners on the Myers-Briggs Type Indicator and the Felder-Silverman Learning Styles Model[24-26,32,33]—work more systematically and slowly than the intuitive learners who are their counterparts. On tests, the sensors read and reread problem statements, often taking a relatively long time to formulate their problem-solving strategies and checking their calculations carefully. This methodical approach will make many of them excellent engineers and experimental scientists, but it frequently leads to their running out of time on long tests. Nothing infuriates students more than studying hard and being well prepared for a test, and then getting a low grade because they lacked sufficient time to demonstrate their understanding. A student who gets a "D" on a one-hour test that he or she could have gotten an "A" on if two hours had been allowed, deserves the "A"; students who do not understand the material at an "A" level will not earn an "A" on the test, regardless of how much time they are given.

Students also resent surprises on tests. The functions of tests are to motivate and help students to learn what the instructor wants them to learn and to enable the instructor to assess the extent to which they have succeeded in doing so. When students understand the material for which they have been prepared but do poorly because they cannot figure out a "tricky" problem on the spot, they see themselves (rightfully) as having been cheated by the instructor.

Thinking and problem-solving skills—and speed in problem solving, for that matter—are only developed through practice and feedback: testing students on skills they have not had an opportunity to practice is unfair. There is neither empirical evidence nor logic to support the argument that long and tricky tests assess students' potential to be successful engineers or help students become better problem solvers. This does not mean that we should construct easy tests, which do not motivate students to learn at a deep level. It is rather to set the bar high, but to teach in a manner such that all students who have the ability to meet the challenge can do so.

***Recommendations*[2,3,69]**

- *Give the students instructional objectives for each test in the form of a study guide. ("In order to do well on this test, you should be able to...")* Make the list comprehensive and challenging. Include objectives that involve all of the basic types of calculations the students should be able to perform, concepts they should be able to explain without using jargon, formulas they should be able to derive, derivations they should be able to explain step-by-step, familiar phenomena that they should be able to interpret in terms of course concepts, and anything else you might call on them to do on the test.[5]
- *When writing the test, consult the instructional objectives and make sure that 10-15% of the test covers the more challenging material in the study guide (which will allow discrimination between the A-level and B-level students).* If the students have the study guide at least a week before the test—and preferably longer than that—and the objectives provide the basis of the test construction, there will be no surprises. The test will be just as challenging, or more so, than it would otherwise have been, except that now the challenge is to the students' conceptual understanding rather than to their speed or puzzle-solving ability.
- *Always work a test out yourself from scratch when you have finished writing it, timing how long it takes to do it.* This burdensome exercise is the *only* way to discover the overspecified and underspecified problems, the erroneous or ambiguous problem statements, the numerical calculations that take large amounts of time but show very little about conceptual understanding, and the appropriateness or inappropriateness of the level of difficulty of the entire test. The alternative is for these problems to show up when the test is being given, which leads to disasters of the type all instructors and students have experienced and do not wish to experience again.
- *Minimize speed as a factor in performance on tests.* For

quantitative problem-solving tests, you should be able to work out the test in less than one-third of the time the students will have to do it, and if the test is particularly difficult or involves many numerical calculations, a one-fourth rule might be more appropriate. If it takes you longer than that, either find a longer time slot in which to administer the test or consider eliminating questions, presenting some formulas instead of requiring derivations, and asking for solution outlines rather than complete calculations.

- *Do not test skills that students have not had a chance to practice.* Don't make all homework problems straightforward calculations and then put deep analysis questions on the test. Don't require numerical solutions on all homework problems and then ask students for qualitative solution outlines on the test. Don't give students problems with extraneous data on the test unless the students have worked on similar problems in the homework. If picking important material from long readings is a skill you want your students to develop, give them training and practice in it—don't just tell them that they are responsible for everything in their 500-page text and make them guess what you plan to ask them to do. If you think ability to solve quantitative problems quickly is an important skill (it is generally not that important in engineering practice), then give the students training and practice in speed-solving in class and on the homework before you make it a primary criterion for doing well on the tests.
- *Even if you curve grades, if the average is in the 50-60 range or below, consider the possibility that it was a poor test or that you did a poor job of preparing the students for it.* If you decide that either is the case, consider adding a fixed number of points to each student's grade to bring the top grade or the average grade to a value of your choosing. Alternatively, if most students missed the same problem, announce a quiz for the following week that will be a variation of that problem and add the results to their test grades.

Justification

Education should not be viewed as a mystery religion. There is no pedagogical value in making students guess what they are supposed to know and understand or in testing them on skills in which they have received no training. When students know explicitly what is expected of them (whether it be straightforward or high-level or ill-defined problem solving, critical or creative or multidisciplinary thinking, or anything else) and they are given practice and feedback in the specified skills, the odds that they will be able to meet the expectations go up. Even though the tests may be harder, the average student performance will be better than it would have been if the tests were exercises in speed and guessing ability, student morale and motivation will increase, and the students who get low grades will be much more inclined to take responsibility for their poor performance than to blame the test or the instructor.

CONVEY A SENSE OF CONCERN ABOUT THE STUDENTS' LEARNING

The social environment in a class—the nature and quality of interactions between the students and the instructor and among the students—can have a profound effect on the quality of learning that takes place in the class.[56,70-75] In his monumental study, *What Matters in College,*[70] Alexander Astin found that the quality of interactions between students and instructors in and out of class was the factor that correlated most highly with almost every positive learning and attitude outcome he considered. If students believe that an instructor is concerned about them and has a strong desire for them to learn the course material, the effects on their motivation to learn and their attitudes toward the course, the subject, and the instructor can be profound. The suggestions that follow are all known to instill such a belief. We suggest that you consider all of them and try to adopt the ones with which you feel comfortable.

Recommendations

- *Learn the students' names.* Taking the trouble to learn names and use them in and out of class conveys a sense of respect for the students as individuals. Their motivation to do well in your course is likely to increase considerably once they realize that you know who they are. Use place cards or seating charts, take and label photographs of the class, or ask students to bring in photocopies of their student identification cards or drivers licenses and use them to help you learn the names quickly.
- *Make yourself available.* Announce office hours and keep them; if you have to miss them, announce it in advance and schedule replacement hours if possible. Encourage students to contact you during your office hours or by e-mail, perhaps insisting that they do so at least once during the first two weeks of the course. Come to class a few minutes early to answer any questions the students may have or just to chat.
- *If you use nontraditional methods such as cooperative learning, explain how what you are doing has been shown to lead to improved learning and/or improved preparation for their careers.* References given in this paper (*e.g.,* Felder and Brent[60]) provide supportive material for such explanations.
- *Celebrate the students' achievements.* When a class does well on a test or you get a number of creative solutions to homework problems, offer commendation. When your students win awards or write articles in the school paper,

congratulate them publicly.

- *Collect periodic feedback and respond appropriately to it.* Collect midterm evaluations, using either simple, open-ended questions (What has helped you learn in the course? What has detracted from your learning? What changes would improve the course for you?) or a more formal instrument, such as a Course Perceptions Questionnaire.[75] Periodically collect "minute papers": at the end of a class, have individual students or pairs take a minute or two to write (anonymously) the one or two main ideas presented in the lecture and the muddiest point or concept. Use the responses to monitor how the class went and to plan the next class. In large classes, use ombudspersons—class representatives who report to you periodically about how well the teaching and learning is going. Regardless of the feedback mechanism chosen, summarize the most common suggestions, share them with the class, accept those you can, and explain why you cannot accept the others.
- *Let students participate in learning and performance assessment.* Give choices on assignments (*e.g.,* problem sets or projects) and tests (*e.g.,* solve any three of the following four problems). Have students critique one another's drafts of assignments or lab reports before the final versions are turned in to you. Let them create potential examination questions, and use one of them on the actual exam. Have them assess their own performance and the performance of their colleagues in team-based projects.[61] Let them contract for the relative weighting of the term work and the final examination.[19,76,77]
- *Maintain a sense of respect for the students, individually and collectively.* Avoid belittling or sarcastic remarks about their responses to questions, performance on tests, behavior in class, or anything else. If you are disappointed with any or all of them, express your disappointment calmly and respectfully. Avoid comments that involve the slightest trace of disparagement or stereotyping directed at students of a particular race, gender, or sexual orientation, or with students who are disabled in any way. If you fail to follow this recommendation, doing everything else recommended in this paper may not be enough to salvage the class.

Justification

The term "caring" or its synonym "concern" show up in virtually every published study of what students consider to be effective teaching. In a review of nearly 60 studies of students' descriptions of effective teachers, Feldman[78] found eight core characteristics in most lists: concern for students, knowledge of subject, stimulation of interest, availability, encouragement of discussion, ability to explain clearly, enthusiasm, and preparation. Factor analysis of rating scales show four generic factors across disciplines: skill (ability to communicate), rapport (empathy, concern for students), structure (class organization, course presentation), and load (workload).[79] No matter what your teaching style may be—flashy or congenial or scholarly—if students believe you care about them, most will be motivated to learn what you are teaching. If you convey a sense of not caring, then no matter how brilliantly or entertainingly you lecture, far fewer will be so motivated.

SUMMARY

We have discussed a wide variety of teaching techniques that have been repeatedly shown to be effective in engineering education. The techniques are variations on the following main themes:

1. Formulate and publish clear instructional objectives.
2. Establish relevance of course material and teach inductively.
3. Balance concrete and abstract information in every course.
4. Promote active learning in the classroom.
5. Use cooperative learning.
6. Give challenging, but fair, tests.
7. Convey a sense of concern about students' learning.

We do not claim that our suggestions constitute a comprehensive list of proven effective teaching methods. Such a list would be encyclopedic and would be comprehensive only until the appearance of the next issue of any journal on education. We also do not claim that adopting all of the suggestions will guarantee that all students in a class will perform at a high level or even that they will all pass. The performance of an individual student in a class depends on a staggering variety of factors, many of which are out of the instructor's control; moreover, an instructor who sets out to implement all of the suggestions in this paper is likely to be overwhelmed in the attempt and to end by implementing none of them.

Our hope is that readers will consider all of the suggestions in the paper in light of their teaching styles and personalities and attempt to adopt a few of them in the next course they teach, and then perhaps a few more in the course after that. While we cannot predict the extent to which the techniques will succeed in achieving the instructors' objectives, we can say with great confidence that their use will improve the quality of learning that occurs in those classes.

IF YOU GET ONE IDEA FROM THIS PAPER

Writing formal instructional objectives and using active and cooperative instructional methods offers a good prospect of equipping your students with the knowledge and skills you wish them to develop.

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Award Lecture . . .

Chemical Engineering Division, ASEE

1999 Union Carbide Award Lecture

PARTICLE DYNAMICS IN FLUIDIZATION AND FLUID-PARTICLE SYSTEMS

*Part 1. Educational Issues**

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The Ohio State University • Columbus, OH 43210

It is indeed a great honor for me to be the recipient of the 1999 ASEE Chemical Engineering Division's Union Carbide Lectureship Award. I am particularly honored to be included among the outstanding educators who have received this award in the past.

Particle technology is not well covered in the chemical engineering curriculum, but it is an important area for chemical engineers from both industrial and academic perspectives. In this lecture I will specifically discuss particle dynamics and will use fluidization and fluid-particle systems as examples to illustrate the importance to chemical engineers of knowing the particle dynamics of these systems.

I would like to define the scope of my lecture as follows:

1. *Observations on educational issues in particle dynamics.*
2. *Comparison of the mechanics of flow of solids and fluids.*
3. *Sample subjects of interdisciplinary nature.*
4. *Sample subjects of pertinence to chemical engineers.*
5. *Computational fluid dynamics of particulate systems.*

In Part 1, appearing here, I will discuss points 1 through 3. I will discuss points 4 and 5 in Part 2, which will be published in the next issue of *CEE.*

OBSERVATIONS ON EDUCATIONAL ISSUES IN PARTICLE DYNAMICS

One of the most important fluid-particle applications in the chemical and petrochemical industries is FCC (fluid catalytic cracking) systems.[1] In North America alone, there are 120 to 135 FCC units in operation, with each processing 40,000 to 50,000 barrels of gas oil per day to generate olefin gas, gasoline, diesel, and heavy cycle gas oil. Approximately 0.08 kg of catalyst are consumed for each barrel of gas oil processed. Figure 1a shows a photograph of a commercial FCC system comprised of a riser reactor and a catalyst regenerator. In the schematic diagram shown in Figure 1b, gas oil is fed into the bottom of the riser in contact with high-temperature catalyst particles recycled from the regenerator to the riser. The gas oil is evaporated, carrying catalyst particles along with it throughout the riser, where cracking reactions take place. The product of the reactions is then sent to the fractionator; the spent catalyst particles are stripped by steam and recycled back to the regenerator.

The solids in this system are processed with gas in various forms or modes. For example, within the riser, gas and solids are in the dilute pneumatic transport mode, whereas within the regenerator, gas and solids are in the dense, turbulent

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Professor Fan is the principal inventor (with R. Agnihotri) of a patented process, "OSCAR," for flue gas cleaning in coal combustion and is the Project Director for the OSCAR commercial demonstration, funded at $8.5 million as Ohio Clean Coal Technology, currently taking place at Ohio McCracken power plant on the Ohio State University campus.

He has served as thesis advisor for two BS, twenty-nine MS, and forty-two PhD students at Ohio State, and is a Fellow of the American Association for the Advancement of Science.

* *Part 2 of this lecture will appear in the Spring 2000 issue of CEE.*

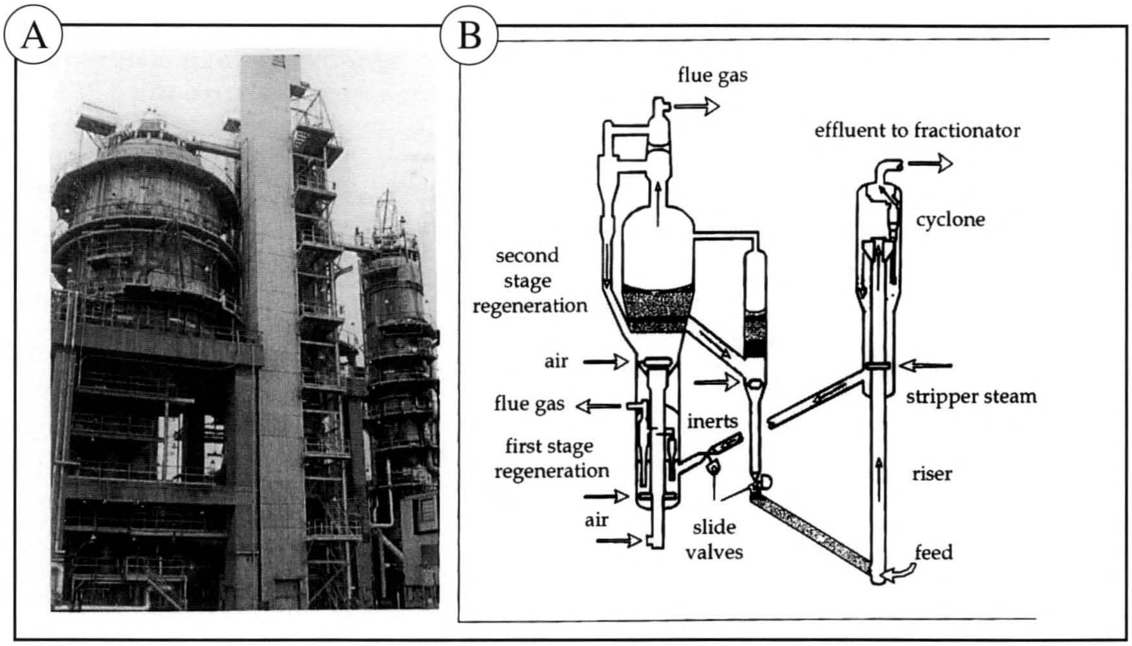

Figure 1.

FCC systems for gas-oil cracking:

(a) Photograph of Equilon (formerly Texaco) commercial FCC unit plant at Los Angeles Refinery (kindly provided by F. Bavarian of Texaco);

(b) Schematic of the system.

fluidization mode. In the catalyst recycle loop, there are dense-phase standpipe solids flow and inclined pipe solids flow.

Solids processing is also involved in chemical synthesis, such as the production of polyethylene/polyolefin. Using the UNIPOL process[2] as an example (see Figure 2), catalyst, cocatalyst, monomer, and comonomer are introduced into a turbulent fluidized bed, where polymerization reactions take place. In the reactor, polymer particles grow in size through chain reactions and eventually reach the final polyethylene size average of 600μm.

Solids processing is also involved in a number of other industries. For example, it is used in physical operations such as powder coating, drying, and mixing. It is also used in energy and environmental systems, e.g., coal combustion and gasification, and incineration of solid wastes, and in metallurgical and mineral processing such as titanium dioxide production. In biological systems it is used, for example, in ethanol fermentation. Overall, solids processing systems are responsible for well over \$100 billion of the chemical and petrochemical market economy annually.

Many students take part in industrial internships and co-op programs. These students and many engineering graduates employed in industry frequently find themselves involved in solids processing, for which they have not been well prepared through regular course work. If we examine the typical undergraduate educational material pertaining to solids processing, we will note that this material is often limited to single-particle behavior (drag, terminal velocity, heat and mass transfer), fixed beds, catalytic and non-catalytic fluid-particle reaction kinetics, and particulate reaction engineering. In the latter, solids particles are often treated the same way as gases or liquids. As a result, the unique characteristics of particle mechanics are not introduced into the analysis of particulate reaction systems. Indeed, very little is discussed on core topics relating to solids processing and particle technology such as

- ▶ Particle characterization
- ▶ Particle formation
- ▶ Size enlargement and agglomeration
- ▶ Comminution and attrition
- ▶ Tribology, friction, and interparticle forces
- ▶ Fluidization and multiphase flow
- ▶ Solids flow, handling, and processing
- ▶ Powder mechanics and slurry rheology
- ▶ Colloids and aerosols

The importance of particle technology education and research was brought to the attention of the industrial and academic communities through the perseverance of such organizations as the American Filtration Society and the Particle Technology Forum of the AIChE in the early 1990s. Subsequent articles in *Chemical Engineering Progress* (*CEP*)[3] and *Chemical Engineering Education* (*CEE*)[4] have contributed to increasing awareness of this topic. As a result

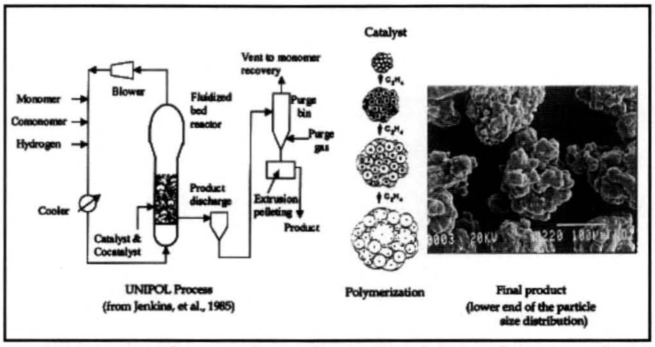

Figure 2. *Chemical synthesis for the production of polyethylene/polyolefin (UNIPOL process).*

Many [co-op students and] engineering graduates employed in industry . . . find themselves involved in solids processing, for which they have not been well prepared through regular course work. If we examine the typical undergraduate educational material pertaining to solids processing, we will note that this material is often limited to single-particle behavior, fixed beds, catalytic and non-catalytic fluid-particle reaction kinetics, and particulate reaction engineering.

of the Fluid-Particle Processes Workshop at the ASEE Summer School for Chemical Engineering Faculty (Snowbird, Utah, 1997), the following articles and reprints related to particle technology education were published in the spring issue of *CEE* in 1998:

- "Teaching Fluid-Particle Processes: A Workshop Report," R.H. Davis, L.-S. Fan
- "Industrial Perspective on Teaching Particle Technology," R.D. Nelson, Jr., R. Davies
- "Particle Technology Concentration at NJIT: An NSF-CRCD Program," R.N. Dave, I.S. Fischer, J. Luke, R. Pfeffer, A.D. Rosato
- "CFD Case Studies in Fluid-Particle Flow," J.L. Sinclair
- "Experiments, Demonstrations, Software Packages, and Videos for Pneumatic Transport and Solid Processing Studies," G. Klinzing
- "Undergraduate Teaching in Solids Processing and Particle Technology: An Academic/Industrial Approach," G.G. Chase, K. Jacob
- "Particle Science and Technology Educational Initiatives at the University of Florida," A.E. Donnelly, R. Rajagopalan

The authors of the articles above are heavily engaged in fluid-particle education and research, and therefore the articles are most pertinent to the point of the present discussion. Recently, federal-, state-, and/or industry-funded research and education centers were formed (*e.g.,* NSF/ERC in Particle Science and Technology at the University of Florida, NJIT/Rutgers State Program on Particle Technology, and the Ohio Board of Regents Universities Consortium on Fine Particle Processing). New web sites (*e.g.,* http://www.erc.ufl.edu/erpt/), new instructional modules (*e.g.,* "Introduction to the Principles of Size Reduction of Particles by Mechanical Means," by Klimpel[5]), introductory textbooks (*e.g., Introduction to Particle Technology,* by Rhodes[6]), advanced textbooks (*e.g., Principles of Gas-Solid Flows,* by Fan and Zhu[7]), and CD-ROMs (*e.g.,* "Laboratory Demonstrations in Particle Technology," by Rhodes and Zakhari[8]) have been published as a result of the growing interest and acknowledged importance of particle mechanics.

I would now like to present some problems that I have noted in my experience in teaching fluid-particle systems that are confusing to students. I will give two examples.

► Log-Normal Distribution

There are three distribution functions that are commonly used to describe particle size distributions, *i.e.,* normal distribution, log-normal distribution, and Rosin-Rammler distribution. The log-normal distribution is particularly confusing to students.

In examining the log-normal distribution, it is noted that it can be expressed in two different equations, depending on whether the random variable is d (Eq. 1) or $\ln d$ (Eq. 2), as given by

$$f_N(d) = \frac{1}{\sqrt{2\pi}\sigma_{dl} d} \exp\left[-\frac{1}{2}\left(\frac{\ln d - \ln d_{50}}{\sigma_{dl}}\right)^2\right] \tag{1}$$

or

$$f_N(\ln d) = \frac{1}{\sqrt{2\pi}\sigma_{dl}} \exp\left[-\frac{1}{2}\left(\frac{\ln d - \ln d_{50}}{\sigma_{dl}}\right)^2\right] \tag{2}$$

Here, d is the diameter of the particle, d_{50} is the median diameter, and σ_{dl} is defined as $\ln(d_{84}/d_{50})$, where d_{84} is the diameter for which the cumulative distribution curve has the value of 0.84. Further, Eq. (2) is the usual expression for the normal distribution with the random variable taken as $\ln d$. The values of $\ln d_{50}$ and σ_{dl} in Eq. (1) or (2) represent the mean and standard deviation of the $\ln d$ distribution, but they are not representative of those of the d distribution. Students are often confused by the two forms of Eqs. (1) and (2) and by the fact that the arithmetic mean of the $\ln d$ distribution is not equal to the arithmetic mean of the d distribution, nor does it equal the natural log of the arithmetic mean of the d distribution; likewise the standard deviation of the $\ln d$ distribution is not equal to that of the d distribution.

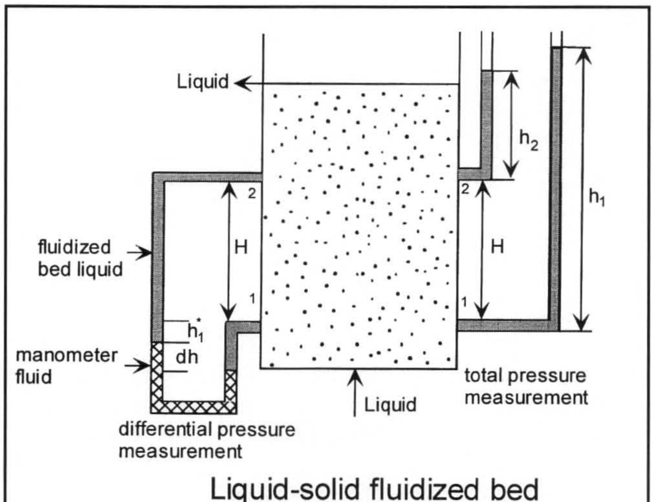

Figure 3. *Pressure-drop measurement for a liquid-solid fluidized bed.*

► ***Dynamic Pressure Drop***

When a manometer is used to measure pressure drop of a suspended particle flow, *e.g.,* a liquid-solid fluidized bed, the pressure drop is measured by $(\rho_m - \rho_l)gdh$ where ρ_m is the density of the manometer fluid and dh is the level difference between the manometer fluid and the liquid in the fluidized bed, as shown on the left-hand side of the manometer arrangement in Figure 3. The pressure drop measured in this manner is known as the differential pressure drop. Students most often question whether the differential pressure drop represents the dynamic pressure drop, ΔP_d, or the total pressure drop ΔP_t, as defined by

$$\Delta P_t = P_{1,t} - P_{2,t} \tag{3}$$

$$\Delta P_d = \Delta P_t - \rho_l gH \tag{4}$$

A force balance on the manometer fluid yields

$$P_{1,t} + \rho_l g\left(h_l^* + dh\right) = P_{2,t} + \rho_l gH + \rho_l gh_l^* + \rho_m gdh \tag{5}$$

Rearranging Eq. (5) gives

$$\Delta P_t - \rho_l Hg = (\rho_m - \rho_l)gdh \tag{6}$$

Thus, we have

$$\Delta P_d = (\rho_m - \rho_l)gdh \tag{7}$$

That is, it measures the dynamic pressure drop.

The total pressure drop can be measured with the manometer open to the atmosphere, as shown in the right-hand side of the manometer arrangement in Figure 3. Frequently, pressure transducers are used for pressure-drop measurements. In this situation, it is essential that proper calibration of the transducer be made so that it reflects the correct type of pressure drop being measured.

Correct identification of either type of pressure drop is important, as they are often used to calculate the volume fraction of the particle, ε_s, or liquid, ε_l, in the bed through the relationships

$$\Delta P_t = (\varepsilon_s \rho_s + \varepsilon_l \rho_l)gH \tag{8}$$

$$\Delta P_d = \varepsilon_s(\rho_s - \rho_l)gH \tag{9}$$

COMPARISONS OF MECHANICS OF FLOW BETWEEN SOLIDS AND LIQUIDS

Phenomenologically, particles and fluids are similar in that they both can flow, but there are distinct differences between their mechanics of flow. For example, particles and fluids respond to stress differently. Solids can transfer shearing stresses under static conditions, while liquids cannot transfer shearing stresses without flowing. For a slow motion of solids, the shear stress varies with the normal stress rather than with shear rate. For a liquid flow, the opposite is true. Solid particles can be consolidated by their cohesive strength induced by internal friction, while there is no internal friction in liquids to sustain their consolidation. Therefore, solid particles can form a heap with a non-zero angle of repose, whereas liquids lie flat under static conditions.

When particles or liquids are placed vertically in a pipe with both ends of the pipe open, the wall shear stress can provide the predominant support for the particle weight. Therefore, to maintain solid particles stationary in the pipe, only a small force needs to be applied to the bottom of the pipe.[9] This is not the case for a liquid. The coherence of the

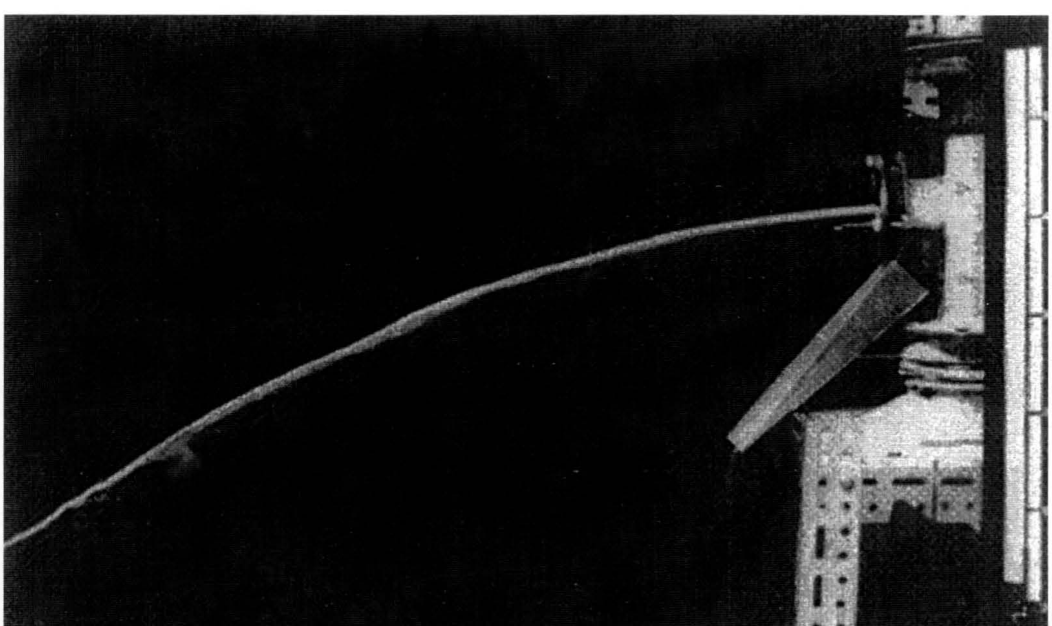

Figure 4.

Particle jet (alumina, 75 μm) formed from a nozzle (3.1 mm in diameter) in an air-fluidized bed (from Martin and Davidson;[10] reproduced with permission).

particles can also be demonstrated by a particle jet[10] when formed from a nozzle in a gas-solid fluidized bed of 75 μm alumina particles, as shown in Figure 4. The coherence of the jet is clearly seen in the figure. The liquid jet from a liquid column is less coherent.

Despite the long history of practice in particle mixing, the phenomena involved remain fascinating and puzzling.[11] Taking the particle band formation in a rotating tube with a binary mixture of particles as an example, a single band or multiple bands would form transiently in a binary mixture of certain particle sizes, weight ratios, and particle volume fractions in the tube. Figure 5 shows single-band and double-band formation of small glass beads (d_p = 0.15 mm, colored white, 30 vol% in the particle mixture) in the presence of large glass beads (d_p = 1.0 mm, colored red, 70 vol% in the particle mixture) with a rotation speed of 60 RPM. The volume fraction of the particle mixture in the tube is 70%. The tube is of 3.1 cm ID and 36 cm in length. The single band forms first and disappears, and then a double band forms. Although some theories, *e.g.*, percolation theory, have been used to explain the particle migration phenomenon, so far there is no overwhelmingly convincing mechanistic explanation of the complex phenomenon exhibited by such a simple experiment.

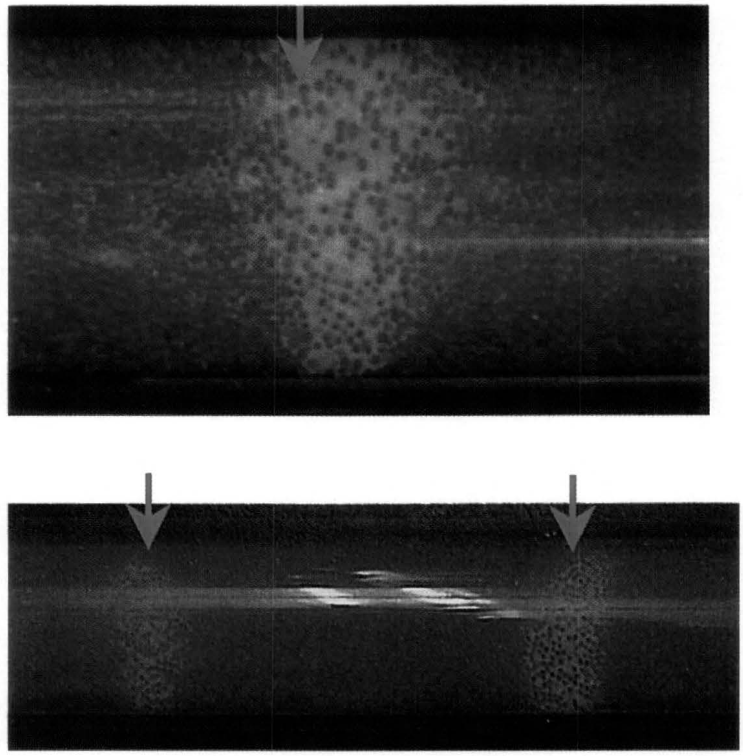

Figure 5. Illustrations of particle-band formation.

SAMPLE SUBJECTS OF INTERDISCIPLINARY NATURE

Probably the most effective way to impart knowledge of such an interdisciplinary topic as particle mechanics to students is through several required chemical engineering courses including fluid mechanics, heat and mass transfer, and reaction engineering, in which clear distinctions can be made between particle and fluid behavior. Once students are vested with the background knowledge relating to particle mechanics, they can choose to take technical-elective courses in chemical engineering or other engineering disciplines that cover some specific aspects of particle-related subjects. In the following, I have chosen hopper and standpipe systems as examples to illustrate the relevance of powder mechanics to a fundamental understanding of powder flow in these systems. These examples are introduced so that students will be familiar with subjects of an interdisciplinary nature.

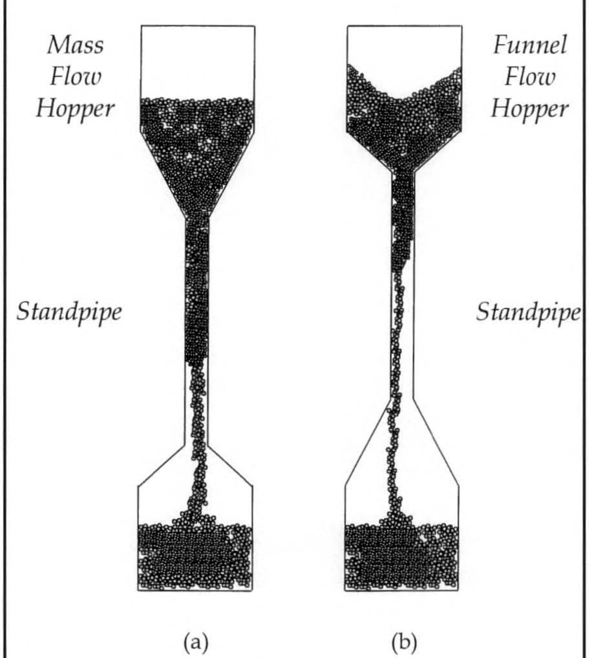

Figure 6. *A device showing mass-hopper flow, funnel-hopper flow, and standpipe flow.*

Hopper and standpipe flows can be demonstrated with a simple experiment. Figure 6 shows a photograph of a device partially filled with table salt. The device has hoppers connected by a standpipe. Figures 6a and 6b show two different hopper flow patterns. For hoppers with a small apex angle (Figure 6a), solid particles flow downward uniformly across the whole cross section, forming a flat surface that is known as a mass-flow hopper. For hoppers with a large apex angle (Figure 6b), solid particles at the central location flow faster than those at the wall, forming a funnel-shaped free surface, known as a funnel-flow hopper. The standpipe flow in the figure shows moving bed transport followed by suspension transport of solids with a larger moving bed region for the mass-flow hopper than for the funnel-flow hopper.

The onset of powder motion in a hopper is due to stress failure in powders. Hence, the study of hopper flow is closely related to understanding the static stress distribution in a hopper.[12] The local distributions of static stresses of powders can only be obtained by solving equations of equilibrium. From stress analyses and suitable failure criteria, the rupture locations in granular materials can be predicted. As a result, the flowability of granular materials in a hopper depends on the internal stress distributions determined by the geometry of the hopper and the material properties of the solids.

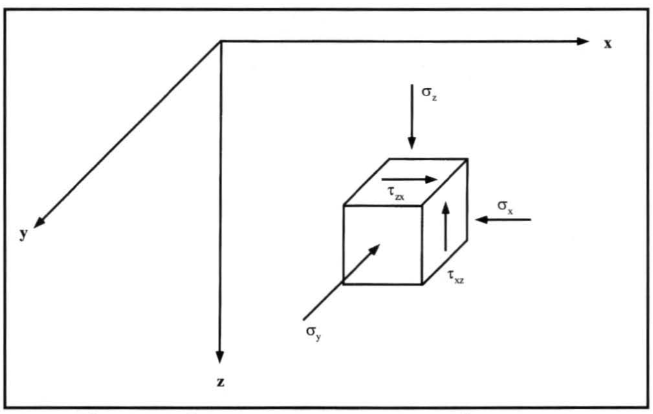

***Figure 7.** Stress components in a plane-strain problem in the x-z plane.*

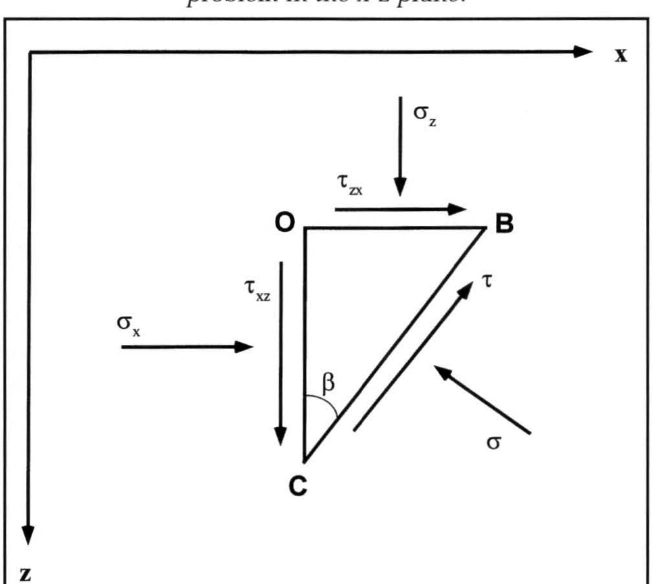

***Figure 8.** Equilibrium of stress components on a differential element.*

Stress analysis of solid materials is a typical subject for engineering mechanists or soil mechanists in civil engineering, but chemical engineers also need to be familiar with the subject in order to be able to quantify moving-bed transport flow of solid particles. Here, students need to learn the Mohr Circle for plane stresses and the Mohr-Coulomb failure criterion, which can be illustrated as follows.

● ***Mohr Circle for Plane Stresses***

We consider stresses on a point represented by a cubic differential element. For simplicity, we examine only the stresses acting on a plane, say the x-z plane, of a cube, as shown in Figure 7. The stress tensor, expressed in Cartesian coordinates, takes the form

$$T = \begin{bmatrix} \sigma_x & 0 & \tau_{xz} \\ 0 & \sigma_y & 0 \\ \tau_{zx} & 0 & \sigma_z \end{bmatrix} \tag{9}$$

where the σ's are normal stresses (compressive stresses are considered as positive), and the τ's are shear stresses. From Hooke's law and assuming no displacement in the y-direction, we have

$$\sigma_y = \nu(\sigma_x + \sigma_z) \tag{10}$$

where ν is Poisson's ratio. In addition, from the conservation of angular momentum, T is found to be a symmetric tensor so that $\tau_{xz} = \tau_{zx}$. Thus, the plane stress tensor in Eq. (9) depends solely on σ_x, σ_z, and τ_{xz}. As shown in Figure 8, the force balance on the differential element results in the stress relationships on the BC plane, as given by

$$\begin{aligned} \sigma &= \sigma_x \cos^2\beta + \sigma_z \sin^2\beta + 2\,\tau_{xz} \sin\beta\cos\beta \\ \tau &= \tau_{xz}\left(\cos^2\beta - \sin^2\beta\right) + \left(\sigma_z - \sigma_x\right)\sin\beta\cos\beta \end{aligned} \tag{11}$$

where β is the angle between the normal of the BC plane and the x-axis. From Eq. (11), two perpendicular planes can be found on which the shear stress vanishes (*i.e.,* $\tau = 0$). The directions of these planes are known as the principal directions and the corresponding normal stresses as the principal stresses. The angle for the principal directions, β_{pr}, is determined from Eq. (11) as

$$\beta_{pr} = \frac{1}{2}\tan^{-1}\left(\frac{2\,\tau_{xz}}{\sigma_x - \sigma_z}\right) \tag{12}$$

which yields the principal stresses as

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_z}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_z}{2}\right)^2 + \tau_{xz}^2} \tag{13}$$

If the principal directions are taken as the x- and z-axes, *i.e.*, $\sigma_x = \sigma_1$; $\sigma_z = \sigma_3$, Eq. (11) reduces to

$$\begin{aligned} &\sigma_x = \sigma_1;\ \sigma_z = \sigma_3 \\ &\sigma = \sigma_1 \cos^2\beta + \sigma_3 \sin^2\beta \\ &\tau = (\sigma_3 - \sigma_1)\sin\beta\cos\beta \end{aligned} \tag{14}$$

which is the equation of a circle in $\sigma - \tau$ coordinates as shown in Figure 9. This circle is known as the Mohr circle. The direction and the magnitude of stresses on any plane can be determined graphically from the Mohr circle. As shown in Figure 9, the normal stresses on the principal planes are of maximum or minimum values.

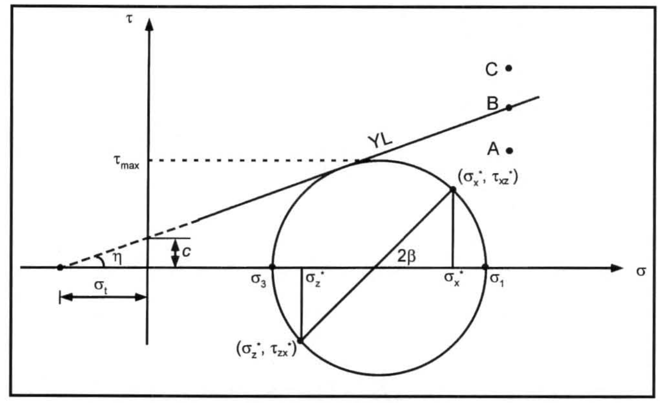

Figure 9. *Mohr circle and Mohr-Coulomb failure envelope.*

● Mohr-Coulomb Failure Criterion and Coulomb Powder

The most common failure criterion for granular materials is the Mohr-Coulomb failure criterion. Based on this criterion, the material fails along a plane only when a critical combination of normal and shear stresses exists on the failure plane. This critical combination, known as the Mohr-Coulomb failure criterion, is given by

$$\tau = c + \sigma \tan\eta \tag{15}$$

where c is the cohesion defined as the resistance of the material to shear under zero normal load and is a result of the intermolecular cohesive forces, frictional forces, and other forces acting on the material, and η is the angle of internal friction of the material, which corresponds to the maximum static friction condition as the bulk solids start to slide on themselves at the state of incipient failure.

The Mohr-Coulomb failure criterion can be recognized as an upper bound for the stress combination on any plane in the material. Consider points A, B, and C in Figure 9. Point A represents a state of stresses on a plane along which failure will not occur. On the other hand, failure will occur along a plane if the state of stresses on that plane plots a point on the failure envelope, *e.g.*, point B. The state of stresses at point C cannot exist since it lies above the failure envelope. Since the Mohr-Coulomb failure envelope characterizes the state of stresses under which the material starts to slide, it is usually referred to as the yield locus, YL.

A rigid-plastic powder that has a linear yield locus is called a Coulomb powder. Most powders have linear yield loci, although in some cases nonlinearity appears at low compressive stresses. The Mohr-Coulomb failure criterion underlies a basic principle that quantifies important hopper design variables such as

- *Critical major principal stress in a stable arc,* σ_a *(see Figure 10)*
- *Hopper (half) apex angle,* φ_w *(see Figure 10)*
- *Minimum outlet dimension of the hopper*

Industrial accidents do occur frequently in hopper flow due to the failure of hopper operators to recognize the stress behavior acting on a stable arc (Figure 10), which blocks the solids flow.

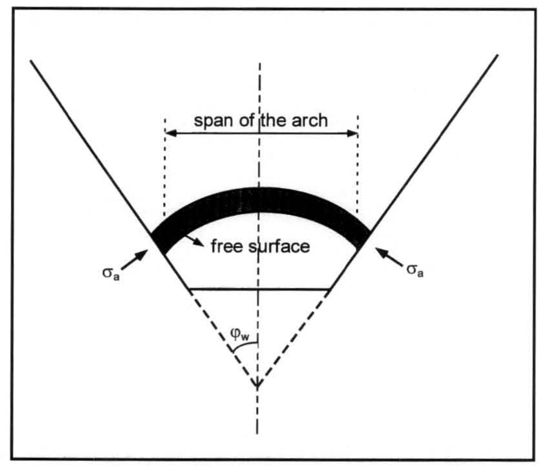

Figure 10. *Arching (or doming) at the hopper outlet.*

● Standpipe Flows

Standpipe flow refers to the downward flow of solids with the aid of gravitational force against a gas pressure gradient. Gas flow is in the upward direction with respect to the downward-flowing solids; relative to the wall, the actual direction of the flow of gas can be either upward or downward.[13] Solids fed into a standpipe are often from hoppers, cyclones, or fluidized beds. A standpipe can be either vertical or inclined, and its outlet can be simply an orifice or can be connected to a valve or fluidized bed. There can be aeration along the side of the standpipe. Frequently, the following assumptions are used in the analysis of a vertical standpipe flow:

- *Both solids and gas are regarded as a pseudocontinuum throughout the standpipe system.*
- *Motions of solids and gas are steady and one-dimensional (in the axial direction).*
- *Solids can flow in either moving-bed mode or dilute-suspension mode. Solids stresses among particles and between particle and pipe wall are considered in the moving bed*

flows but neglected in the dilute suspension flows.

- *The gas can be regarded as an ideal gas, and the transport process is isothermal.*

The cylindrical coordinate system selected for the standpipe is shown in Figure 11. For a one-dimensional steady motion of solids, the momentum equation of the particle phase can be written as

$$\rho_p(1-\alpha)u_{zp}\frac{du_{zp}}{dz}=\rho_p g(1-\alpha)-\frac{d\sigma_{pz}}{dz}-\frac{2\tau_{pw}}{R_s}+F_D \quad (16)$$

where α is the volume fraction of the gas phase; σ_{pz} is the normal stress of solids, τ_{pw} is the shear stress of solids at the pipe wall, F_D is the drag force per unit volume, and R_s is the radius of the standpipe. As solids flow can be in either a moving packed bed mode or a suspension transport mode, Eq. (16) can be simplified as

- *For a moving packed bed mode,* α *is constant.*
- *For a suspension transport mode,* σ_{pz} *is negligibly small.*

The general momentum balance for the gas phase can be expressed as

$$\frac{dp}{dz}=-F_D \quad (17)$$

where p is the pressure.

For a simple standpipe system, different flow patterns of steady flow may exist, depending on the ranges of operational parameters of the system. This phenomenon is known as steady-state multiplicity.[14] The steady-state multiplicity is considerably more complicated when gas aeration takes place from the side of a standpipe for controlling the solids flow rate. Such gas aeration is common in industrial operation.

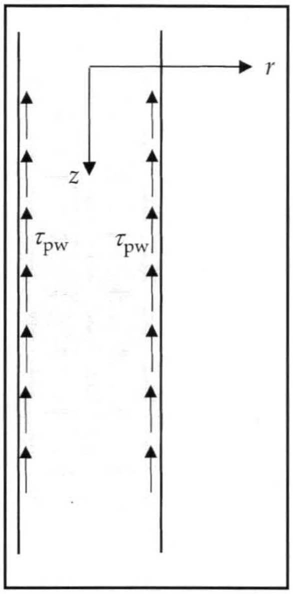

Figure 11. *Coordinate system for one-dimensional standpipe flow.*

CONCLUDING REMARKS

I would like to conclude this part of my lecture with the following thoughts:

- *Particle technology as exemplified by fluidization and fluid-particle systems is an important interdisciplinary area. Chemical engineers play a key role, as there are many industrial applications in the chemical process industries.*
- *Education in particle technology is important from both the industrial and the academic perspectives. Significant progress in education and research in this area has been made recently, such as increased textbook publications and increased industrial recruiting of U.S.-educated graduates—but much remains to be done.*
- *The most effective way to introduce particle technology materials to chemical engineering students is through such existing required courses as transport phenomena and reaction engineering.*

ACKNOWLEDGMENTS

This lecture is dedicated to the memory of Professor Shao-Lee Soo of the University of Illinois, Urbana. I am grateful to Prof. Fernando Muzzio for insightful discussions on powder mixing and band formation, and to Dr. Fashad Bavarian for providing the FCC unit photograph used in Figure 1 and the information concerning commercial operation of FCC units. I am also indebted to Prof. Jack Zakin and my research group members, Dr. Jianping Zhang, Mr. D.-J. Lee, Mr. Brian McLain, Mr. Will Peng, and Mr. Guoqiang Yang, who have provided constructive feedback in the preparation of this lecture material.

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TOWARD TECHNICAL UNDERSTANDING

Part 4. A General Hierarchy Based on the Evolution of Cognition*

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As their principal role, institutions of higher learning are to develop and extend those high-level cognitive skills that people need to function productively in modern society.[1] Such skills include complex abstract thought, logical and mathematical reasoning, synthesis and analysis, and the ability to recognize and apply patterns, generalizations, theories, and schema to solve problems. Such skills are developed by immersing students in a community whose members explicitly attempt to pass those skills to other segments of the society. This difficult job is attempted only at institutions of higher education. But though we, as institutions, have been at this job for centuries, we still do not have effective methods for accomplishing it.

In previous papers in this series, I presented a hierarchy of technical understandings[2,3] based on my experience in trying to help students learn and on our current knowledge of the structure and function of the human brain.[4] I will refer to this as a *special* hierarchy of understandings.

But in addition to using observations of college students and brains to obtain evidence for how learning occurs, we can also pursue other routes. For example, Merlin Donald studied the evolutionary history of culture from apes to *homo sapiens sapiens* to show how high-level cognitive skills probably developed.[5] And in another study, Kieran Egan used mental growth in youngsters as the basis for a theory of how humans learn.[6] Both these studies result in cognitive hierarchies. That by Egan contains five levels of human understandings: somatic, mythic, romantic, philosophic, and ironic. I will refer to this as a *general* hierarchy of understandings.

In this general hierarchy, it is the philosophic level that encompasses the critical thinking skills required of engineers. However, we cannot immediately begin instruction at the philosophic level, because the special and general hierarchies are not merely sequential, but integrative: in such models, mastery at any level requires assimilation, reorganization, and generalization of understandings gained at lower levels. Hence, unless students have attained adequate facility with somatic, mythic, and romantic thinking, they cannot progress beyond a superficial level of philosophic understanding. Unfortunately, most students now entering engineering schools in the U.S. are ill-prepared to develop technical understandings at the philosophic level. Moreover, various strategies currently in vogue for addressing this problem—such as problem-based learning, discovery-based learning, group work, and web-based learning—are primarily attempts to exercise thinking at the philosophic level. As such, they fail to meet student needs at lower levels in the hierarchy and therefore they are generally not as effective as they could be. For some students, such learning exercises are, in fact, counterproductive.

As engineering instructors, we are masters of philosophic understanding, and we naturally want to teach what we do best. But many engineering students are not prepared to enter into philosophic modes of instruction. If those students are not properly prepared, then philosophic instruction is largely frustrating, and such students fail to develop the skills we want them to have: ability to solve novel problems, ability to extract meaning from data, ability to develop technical narratives that are well-reasoned and convincing, abil-

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* *Part 1, "Brain Structure and Function," CEE, Vol. 31(3), 152 (1997); Part 2, "Elementary Levels," CEE, Vol. 31(4), 214 (1997); and Part 3, "Advanced Levels," CEE, Vol. 32(1), 30 (1998).*

ity to exercise sound engineering judgment. The question is, can we do anything about it?

EPISODIC LEARNING

Before identifying levels of human understandings, we consider the demarcation between human and animal cognition. In animals, the highest levels of cognitive skills are found in chimps and the great apes. Beyond the instinctive and procedural-habits characteristic of all animals, chimps and great apes are masters of the moment; they can contrive creative solutions to problems as they arise. For example, they can combine available objects in new ways and they can use available objects as tools to achieve goals. Further, some individual apes have been taught a subset of American Sign Language.[7] Donald refers to these achievements as *episodic* learning. These kinds of achievements are remarkable; nevertheless, they are limited to the current situation—animals live in the present. They do not plan for the future. For example, they do not make tools of their own. Although they may have used an object repeatedly as a tool, they do not set it aside for future use. Even though they may learn some sign language, they have never made original contributions to their vocabulary, much less created a grammar. In short, animals with the most highly developed cognitive skills appear incapable of abstract thought.

> ***. . . the special and general hierarchies are not merely sequential, but integrative: in such models, mastery at any level requires assimilation, reorganization, and generalization of understandings gained at lower levels.***

SOMATIC UNDERSTANDING

The first step beyond episodic learning is prelanguage and relies on the sense of touch to gain and convey understanding. For engineers, its important characteristics are tactile learning, toolmaking, and communication by manual gestures and body motions. Donald calls this *mimetic* learning, but we follow Egan and call it *somatic* understanding. At the somatic level, we have already taken a decisive step away from episodic learning and into abstract thought. Thus, the touching and manipulating of objects, which is characteristic of tactile learning, seem to aid the human mind in learning to create abstract images. We conjecture that mastery at the somatic level is a prerequisite for later facility with highly abstract thought. Thus, Newton was an accomplished experimentalist before he wrote the largely theoretical *Principia,*[8] Gibbs designed gears and brakes for railway cars before he developed the abstract thermodynamics of phase equilibria,[9] and (to stretch the point only slightly) Einstein worked with concrete inventions submitted for patent before he developed the theory of relativity.[10] The close interdependence of manual dexterity and abstract mental processing has been emphasized in a book by Frank Wilson;[11] similarly, the connections between manual skills and engineering talents have been emphasized in an article by Petroski.[12]

Toolmaking, which reverses tactile learning, is the attempt to convert abstract images into concrete objects. Toolmaking is taught in master-apprentice relations with little verbal communication; the instruction relies heavily on gestures, physically realized procedures, and concrete trial-and-error strategies. An enhanced remnant of this somatic mode of instruction serves as the basis for today's graduate education.

Somatic modes of communication rely on manual gestures and body motions—obvious abstractions employed to convey ideas and relations among concrete objects and situations. There is a growing body of evidence to support Donald's position that human language evolved from manual gestures.[13] Further, somatic forms of communcation are still employed in the performing arts, in sign languages for the handicapped, and in signals used by referees and umpires in sporting events.

An instructive example of somatic learning has been documented in a recent article published in this journal;[14] as a student, S. Godiwalla found herself frustrated by instructors who consistently presented engineering subjects at high levels of abstraction. She needed to see the pumps, valves, and fittings that were being represented symbolically in lectures; to understand, she needed to handle the objects, look inside them, take them apart. Her response was to find a technician who could help her convert abstract symbols into concrete reality. It is germane to note that Ms. Godiwalla was a double major in chemical engineering and dance; thus, we have strong evidence for a student functioning at the somatic level.

MYTHIC UNDERSTANDING

In evolutionary terms, mastery of somatic skills serves as a foundation for creating abstract names for concrete things, then language, and then names for abstract things such as virtue, patience, and deceit. Understandings at this level are characterized by oral traditions, such as myths and epic poetry, and so they can be called *mythic* understandings. In an earlier paper in this series,[2] I discussed the power that primitive people attributed to names. That power becomes extended and generalized when myths are used to explain

Once a culture has established an oral tradition, it may proceed to further levels of abstraction by creating graphic images for objects, situations, and events. Such pictures, hieroglyphs, and other graphic devices may be followed by creation of symbols for numbers, an alphabet, and writing.

how the world works. At the mythic level, understandings are developed and conveyed through stories: oral structures composed of an introduction that establishes a conflict, an internally consistent narrative line, and a conclusion that resolves the conflict. Egan reminds us that Carl Sagan and Richard Feynman were both masters at presenting technical material in narrative forms.[6]

To establish such narratives, storytellers usually create conflicts based on binary opposites: good vs. bad, strong vs. weak, industrious vs. lazy. For us as sophisticated instructors, this is a simple-minded way to view the world; further, it leads to two-valued logic systems that are not merely wrong, but dangerous.[15] (For example, "Never trust anyone over 30." "All Democrats are liberals." "People who can't do, teach.") Nevertheless, binary opposites are effective for introducing new ideas, and they allow us to develop narrative lines that conclude with discussions of engineering judgment. In technical material, binary opposites rarely occur, but the same advantages can be obtained by appealing to binary alternatives; for example, we might introduce chemical processes as either batch or continuous, instruments as either digital or analog, and pumps as either centrifugal or positive displacement. The degree to which such a pair fails to cover all possibilities would be left for later discussions at higher levels of understanding.

ROMANTIC UNDERSTANDING

Once a culture has established an oral tradition, it may proceed to further levels of abstraction by creating graphic images for objects, situations, and events. Such pictures, hieroglyphs, and other graphic devices may be followed by creation of symbols for numbers, an alphabet, and writing. Note that graphic devices and writing involve abstractions identified at the mythic level combined with manual dexterity developed at the somatic level. This particular combination of manual and mental abilities may have prevented some cultures from converting their oral traditions into written language. Thus, some cultures remained at the mythic level, while others developed graphic expression without adding a written language. Graphics, numbers, and writing bring a richness and flexibility that is missing from the somatic and mythic levels; however, these advantages come at the price of greater difficulty in attaining mastery at this level.

It is a command of graphic symbols and writing that characterizes *romantic* understanding, so called because the explanatory stories of mythic understanding are converted into stories driven by human needs and aspirations. One aspect of romantic understanding is an emphasis on bounds—on the limits of human performance. Thus, at the romantic level, we focus on the highest building, the longest bridge, the fastest car, the most powerful rocket engine, and the smallest (nanoscale) motor. The seven wonders of the ancient world were all made by man.

To illustrate the human context of a technical topic, let us consider using the romantic mode for introducing the second law of thermodynamics. In so doing, we would not merely introduce such abstractions as entropy, irreversible processes, and heat engines, we would place those abstractions within the context in which they were invented: the needs driven by the industrial revolution occurring in Europe in the early 1800s. To humanize the discussion, we could discuss the personal histories of such figures as Sadi Carnot in France, Rudolf Clausius in Germany, and William Thomson (later Lord Kelvin) in Britain, whose efforts culminated in a formal statement of the second law.

A second aspect of romantic instruction is that material is not presented in a linear sequence; rather, the presentation emphasizes salient points and ignores details. To illustrate, Egan uses the metaphor of map-making. If we were to take a romantic approach to mapping a country, we would not proceed systematically from one coordinate to the next; instead, we would locate the prominent features—the mountains, lakes, rivers, canyons, gorges, and cities. Adding details involves understandings beyond the romantic. We find it convenient to extend this metaphor by referring to the "object" defined by this romantic activity as the conceptual *landscape* for a topic.

A third aspect of the romantic mode is the uncovering of interesting and unexpected connections. For example, Sadi Carnot's work on heat engines was influenced by the interests of his father, Lazare Carnot, who was minister of war under Napoleon in 1800 and minister of the interior during Napoleon's Hundred Days in 1814. When war erupted between France and Britain in 1792, France faced a possible shortage of pencils. It was Lazare Carnot who commissioned Nicolas-Jacques Conté to develop a process for making high-quality pencil lead from low-quality graphite.[16] By about 1794, Conté had succeeded in inventing the *crayons*

Conté, which are essentially our "lead" pencils. Thus, the second law of thermodynamics is circuitously connected to an instrument that contributed to writing and, hence, to the spread of romantic understandings.

Connections are often interesting because they are counterintuitive or amusing. For example, modern textbooks routinely use the second law to prove that there can be no perpetual motion machine. But it is amusing to note that Sadi Carnot reversed the logic: he deduced the second law from the assumption that perpetual motion machines cannot exist.[17] Such connections serve as themes for popular essays written by James Burke and now regularly published in *Scientific American.*

Besides bounds, connections, and human interest, the romantic level invokes pictorial symbols: diagrams, flowsheets, plots, and other figures that are characteristic of engineering. At first blush, there may seem to be little to say about these devices—they are taken for granted in both engineering education and practice—but for this very reason, they may be easily misused in teaching. First note that although plots are romantic devices, they may invoke interpretations at other levels of understanding. For example, some plots can be interpreted in terms of the performance of equipment; this appeals to somatic understanding. On other plots, a curve might be interpreted in narrative terms as illustrating a response to conflicts or competition between variables; this appeals to mythic understandings. Still other plots may be interpreted as expressing relations among terms and quantities in equations; this appeals to philosophic understandings, as discussed in the next section. Thus on entering the romantic mode of learning, a student may readily understand some plots, but have difficulty with others.

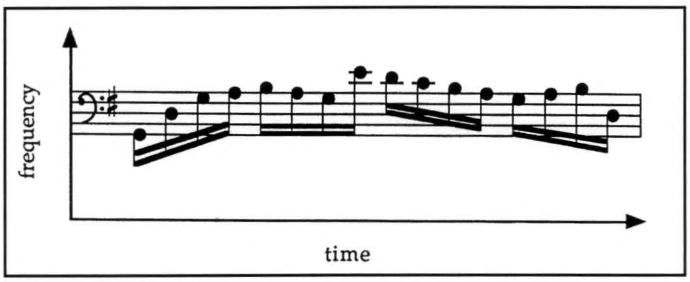

***Figure 1.** The x-y plot is a graphic device characteristic of those deployed at the level of romantic understanding. Nevertheless, such plots are late inventions in human history, coming long after romantic, philosophic, and ironic understandings were fully developed. The first x-y plot was apparently the musical staff, created by a Benedictine choirmaster during the Middle Ages.[18]*

Second, note that *interpreting* an existing plot usually involves lower levels of understanding than those used in *creating* the plot. For example, the first x-y plot was, apparently, the musical staff created by Benedictine monks during the Middle Ages;[18] on the staff, pitch (frequency) of each note is plotted on the ordinate, while time runs along the abscissa, as shown in Figure 1. The musical staff is a graphic—a romantic—device created by philosophic thinking for use by mythic performers. Nevertheless, creation of a plot can involve somatic elements that are beneficial to some students; they gain understandings by manually transforming a table of data onto graph paper. This benefit is lost when we force all students to construct plots on computers, for somatic contact with the data is replaced by representations and manipulations at higher levels of abstraction.

PHILOSOPHIC UNDERSTANDING

To our knowledge, all human cultures developed somatic knowledge and mythic traditions and some developed romantic learning, but few developed *philosophic* understandings; in fact, we know of only one such culture—the ancient Greek. At the philosophic level, the graphic tools and written language mastered at the romantic level *may* enable development of higher-order thinking skills: inductive and deductive logic, inferential reasoning, analysis and synthesis, critical thinking, creation of theoretical constructs, and generalizations. These abstractions relate, simplify, and extend knowledge gained at lower levels in the hierarchy.

Our experience implies that the transition from romantic to philosophic understandings is a difficult one; in fact, individuals do not seem able to make the complete transition by themselves.[6] That is, to progress beyond a superficial level of philosophic understanding, an individual must reside in a community of philosophic and ironic thinkers and learn from them. This is *the* principal role of higher education in our society,[1,6] although the role is poorly understood by most students, many administrators, and some faculty.

To achieve technical understandings at the philosophic level, we rely heavily on mathematical logic using equations. An equation is a romantic construct: a collection of graphic symbols arranged to show relations among quantities and ideas. But even at this romantic level, many students have difficulty distinguishing equations from formulae: formulae are means for converting numbers into other numbers (such is the use of the quadratic formula), while equations are means for expressing relations. Of course, most equations can also be used as formulae, but their real import lies in relating ideas, not numbers.

The *use* of equations in developing mathematical chains of logic, however, is not a romantic activity, but rather a philosophic one; examples include proofs, derivations, and the deductions routinely employed in problem solving. Such activities are highly abstract and require substantial sophistication on the part of the student. As instructors, our tendency is to underestimate the somatic, mythic, and romantic skills that students must have mastered before they can manipulate equations productively at the philosophic level. As Marvin Minsky has noted, "it takes years to become proficient at the language of mathematics."[19]

In addition to mathematics, we have a host of other devices for developing and conveying philosophic understandings; examples include problem-solving strategies, operating procedures, technical reports, computer programs, generalized patterns (such as the unit operations), and generalized theories (such as occur in transport phenomena). Such philosophic devices are routinely explored and exploited in our teaching and in this journal, so there is no need to belabor them here.

Philosophic understandings develop from systematic explorations of a subject's conceptual landscape. In such explorations, we seek justification for the prominent features identified at the romantic level; further, we seek to expose the logical connections—the details— that relate the prominent features. But such an exploration soon overwhelms us with the innumerable details that establish the often-complex web of connections among important points. To maintain control over the material, we seek simplifications via overriding patterns, theories, schema, and generalizations that organize our knowledge into structures that are useful; in the words of Mach, we seek *economy of thought.*[20]

The reorganization of knowledge into abstract and economical structures is the characteristic activity of learning at the philosophic level. Following Vygotsky, we can divide this activity into four steps:[21]

1. *Conceptualization,* which is the creation or recognition of a concept that arises from observing concrete situations. For example, placing a pan of water on a hot stove might lead us to the concept of heat as an explanation for the observed temperature rise. Conceptualization may take place at mythic, romantic, or philosophic levels; often, it incorporates features from all three.
2. *Transference,* which is the use of the concept to solve problems in concrete situations other than the one that inspired conceptualization. Thus, continuing with our example, when we place the pan of water in a refrigerator, we might again use the concept of heat, now to explain the fall in temperature.
3. *Generalization,* which is creation of an abstract interpretation of the concept, independent of any concrete object or situation. Thus we might eventually generalize the concept of heat to the more abstract notion of energy: heat is a form of energy that "crosses" system boundaries. Exploration of the generalized abstraction might lead us to generalized rules; for example, whenever the net effect of a process is to add energy to a system, we expect temperature to rise.
4. *Extension,* which occurs whenever we recognize concrete situations, unlike those in conceptualization and transference, to which the abstract form of the concept can be applied. For example, we place ethanol in an insulated vessel and then do work on it. We understand that the temperature will rise because we have added energy, even though no heat crossed the boundaries.

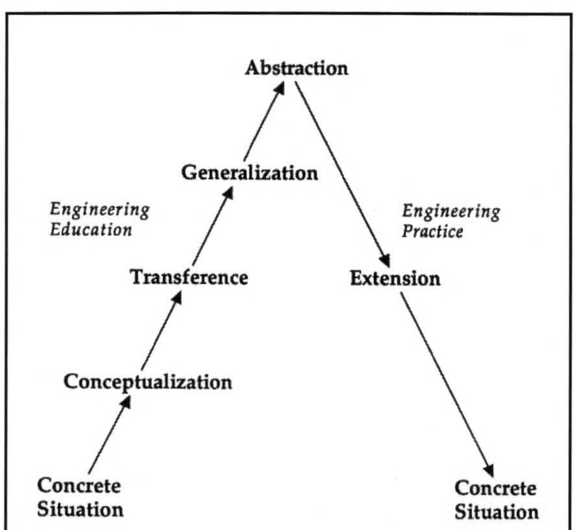

Figure 2. *Psychological studies of learning[21] and neurological studies of brain function[2-4] confirm that student understandings of abstractions develop in a bottom-up learning strategy from concrete situations to abstract concepts. Thus, it is counterproductive to attempt to teach conservation of energy by confronting students first with the generalized energy balance. However, we apply abstractions in a top-down fashion, from abstract notion to concrete situation. Thus in problem solving, students should be taught to start with the generalized energy balance and then proceed deductively.*

The articulation of these steps helps us recognize a possible pitfall when using standardized tests to assess student progress. It is relatively "easy" to drill students in conceptualization and transference, so they can perform well on standardized tests, but without the ability to generalize and extend what they know, such students remain confined to a rather superficial level of philosophic understanding.

Note that, as illustrated in Figure 2, we *develop* understandings of abstractions by instructing in a bottom-up mode: concrete situation to abstraction. But, we *apply* abstractions in a top-down mode: abstraction to concrete situation. These two strategies, bottom-up for engineering education and top-down for engineering practice, were deduced from Vygotsky's psychological studies of language acquisition in children;[21] but we emphasize that they are consistent with our earlier deductions about proper learning strategies based on the current understanding of brain function.[1-3] Note also that as students develop and practice these skills, they often find extension, the transition from abstract to concrete, to be just as difficult as generalization, the transition from concrete to abstract.[21]

Finally, we must emphasize the dangers that are inherent in the power of philosophic understandings: the command of knowledge and economy of thought provided by patterns and generalizations can easily seduce any of us into self-deception.

We are particularly susceptible to self-deception at two levels of philosophic development. One occurs at the novice level, where the student's knowledge base is small, so nearly *any* theory or generalization can organize and explain situations and events.[6] The mild form of this disease leads to overconfidence: the student considers his understanding complete, so filling in details is considered to be an unnecessary waste of effort. More severe cases lead to mental stagnation, prejudice, and antisocial behavior.

The second window of susceptibility comes with mastery of philosophic understanding of a particular, well-defined and usually narrow, portion of a discipline. Though the domain of knowledge may be small, it still requires years of effort to master, so that although success is a true accomplishment, it may induce self-deception manifested as hubris. A common symptom is the expectation that the patterns, generalizations, and organizing principles found in the restricted domain must apply to other domains; if they do not, then those other domains are deemed unimportant and can be ignored. Thus, we have scientists who treat humanists with disdain, and humanists who treat scientists with contempt. Such narrowly trained experts can pose considerable dangers to a society, as was emphasized long ago by Ortega y Gasset.[22]

IRONIC UNDERSTANDING

If we are able to avoid or overcome self-deception, and if we gain sufficient facility and experience with manipulating knowledge at the philosophic level, then we may come to realize that even the power of philosophic understanding is limited. Any real situation is so complex that it is, at best, only incompletely described by our abstractions, theories, and generalizations; in fact, many real situations are not described by *any* of our hard-won theoretical constructs. Such realizations may drive us to a level of understanding that Egan calls *ironic*.[6]

One aspect of ironic understanding is a proper perspective on models; all our attempts to describe and explain reality are merely models. At the somatic level, we use the human body in our first crude attempts to model. At the mythic level, the myths themselves serve as modeling devices.[5] At the romantic level, graphics and writing allow us to revise the simple models of myths into more elaborate structures. At the philosophic level, technical thinking is dominated by mathematical models; at this level, we think we know much. The transition to the ironic level starts when we realize we still know very little.

As engineering instructors we are probably more comfortable than most with the roles that models assume in contributing to and limiting our understandings. As engineers we routinely justify the use of a particular model in a given situation by the *a posteriori* observation that it solved the problem. "Whatever works" is laden with ironic overtones. Nevertheless, engineering students have considerable difficulty in recognizing models, in accepting their limitations, and in selecting the appropriate model for a given situation. For many students, "whatever works" is a cop-out rather than a signal of subtle sophistication.

Another aspect of a properly developed ironic understanding is an underlying sense of humor. To have successfully completed the transition from the romantic to the philosophic level, to have spent years in mastering a discipline at the philosophic level, and then to realize that one still knows little—such progression must drive an individual to either despair or to humor. To react with humor is to recognize and accept the irony of our lot.

More generally, the ironic thinker is sensitive to anomalous situations that fail to adhere to the usual philosophic patterns and theories. Such thinkers display considerable insight in attaching abstract interpretations to concrete phenomena, flexibility in manipulating concepts, and judgment in combining models with formal theories. Ironic thinkers are comfortable with multiple solutions, the lack of solutions, ambiguity, uncertainty, and doubt.

It is probably too much to expect that in four years we can bring many engineering undergraduates to even an operational understanding at the ironic level; nevertheless, we can sow seeds for future growth. In our instruction, we can continually emphasize the roles and limitations of models, and we can give students exercises that force them to select the model most appropriate for a given situation—such exercises develop engineering judgment. To illustrate that many situations have no single "right" answer, we can confront students with open-ended problems; further, any problems having multiple solutions allow us to illustrate the consequences of manipulating a situation to achieve different objectives.

Finally, we can exploit humor as an instructional device. Elsewhere I have speculated about the probable relations between humor and creativity.[3] Here it is appropriate to twist an observation of Minsky's:[19] at the philosophic level, engineering instruction is essentially the humorless activity of using mathematical logic to establish connections, but ironic instruction contains a humorous element that relaxes constraints and allows the mind to seek unconventional connections. Both modes of instruction are needed to start students toward understandings at the ironic level.

CORRESPONDENCE BETWEEN THE SPECIAL AND GENERAL HIERARCHIES

In this section we point out that the hierarchy of technical understandings, introduced previously,[2-4] corresponds to the general hierarchy,[6] which is described in the previous sections. In fact, the technical hierarchy is a subset of the more general one; this is illustrated in Figure 3.

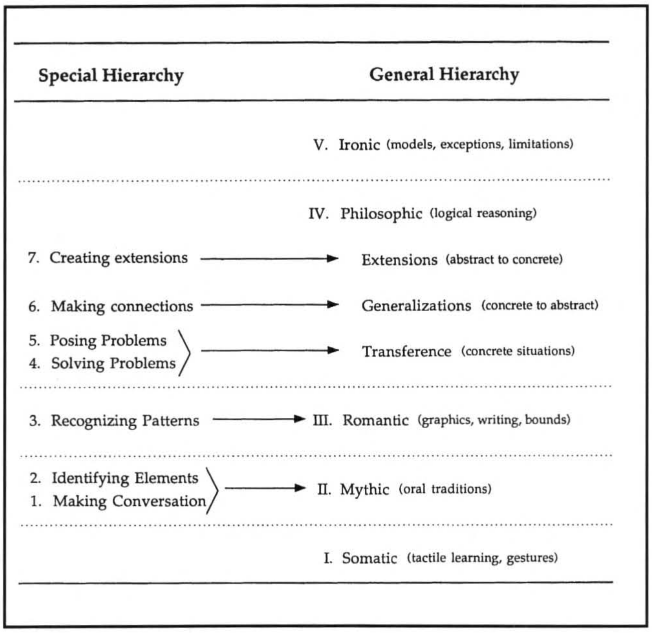

Figure 3. *The hierarchy of technical understandings (left) introduced previously[2-4] is a special case of the more general hierarchy (right) developed by Egan.[6]*

The technical hierarchy begins, at its most elementary level, with *making conversation,* and it continues with articulation of definitions that *identify conceptual elements.* These activities are fundamental to the oral traditions characteristic of mythic understanding, for conversation leads to storytelling, and both conversation and storytelling reveal the need for a language composed of words having commonly accepted definitions.

The third level in the technical hierarchy is *pattern recognition;* at this level we attach meanings, rather than mere definitions, to a concept by relating it to other concepts. The pattern formed in this way defines the conceptual landscape, which is a product of romantic understanding.

The fourth and fifth levels of the technical hierarchy involve *problem solving* and *problem posing.* These are the principal activities that constitute transference of concepts among concrete situations in philosophic understanding. *Making connections,* at the sixth level of technical understanding, is the same as the philosophic exercise of generalizing concepts from concrete situations to abstract ones.

Finally, at the seventh level of technical understanding, *creating extensions* is the philosophic activity of applying abstractions to different concrete situations. Thus, we have a close and satisfying correspondence between the technical hierarchy and the more general one.

In the next paper in this series we will discuss how the general hierarchy can be applied to engineering education.

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Separation Process Technology

By *Jimmy L. Humphrey and George E. Keller II*
Published by McGraw-Hill, New York, 408 pages including index, $54.95 (1997)

Reviewed by
Phillip C. Wankat • Purdue University

This is a book of tips, industrial applications, practical flow sheets, new developments, and some theory, including empirical expressions for industrially important separations in the Chemical Process Industry (CPI). It contains a significant amount of useful information gathered by the authors during their years in consulting and industry—I took 19 pages of hand written notes while reading it.

The separations considered are those that are commercially important within the CPI, with an emphasis on separation at the molecular level. Thus, distillation and its variants, extraction, absorption/stripping, adsorption, and membrane separation processes are covered in detail. The sections on distillation, absorption/stripping, and adsorption appear to be most authoritative. Mechanical separations such as settling, cyclones, centrifuges, filtration and magnetic separators are not included. Processes that have some importance in the CPI or are important in other industries, such as flotation, crystallization, electrophoresis, and chromatography (except for simulated moving bed systems), are also not covered.

Although not a textbook (the authors assume the reader understands basic theories and there are no homework problems), this book is an excellent resource for professors who teach separations. The authors discuss the latest commercial advances and present a variety of applications; many tables and figures collect useful information. Examples can be used to provide a practical, industrial flavor to lectures. There are useful ideas for the size ranges employed in industry for different separations. The presentation is also particularly good on rules of thumb that predict when to use particular separations. For example, the authors compare air separation alternatives such as adsorption versus cyrogenic distillation versus membranes. They clearly keep economics in mind throughout the book. They note that the value of the exponent in the "six-tenths" power rule explains why distillation scales up well but doesn't scale down well, and why membrane separations do the opposite. They discuss new separation devices such as membrane contactors for absorption/stripping. Other examples include the extensive discussions on new trays and structured packings.

For all its strengths, this book does have a few weaknesses. Some of the flow sheets (*e.g.*, Figures 2.51, 2.59, and 5.22c) are clearly missing streams since they are not possible as drawn. The selection of topics is occasionally mystifying (*e.g.*, the new rate analysis of distillation columns is predicted to eventually replace equilibrium analysis, but the former is ignored while the equilibrium staged analysis is explained in detail). There are a few places where the book is a core dump instead of being fully digested. For example, on p. 143 a figure and table from different sources presenting extractor efficiency data don't agree, but the authors do not comment on this discrepancy. In addition, some of the practical wisdom, such as "Although HTU is more rigorous, HETP is used more frequently," may not sit well with professors. These are really minor points considering the practical information and useful features in this book.

A wealth of practical information not available in textbooks is included. For example, the authors state that composite polymer membranes may have the dense layer separate from the support layer if they are back flushed. This ruins the membrane and should normally be avoided. The authors have collected a number of empirical equations that give useful shortcuts. Examples include estimates of HETP, the flooding pressure drop from the packing factor, the minimum L/D, and the reboiler heat duty.

Additional useful features include tables of resources for VLE data and predictions; an annotated list of suppliers of simulation programs; a large number of references; an index; and appendices that include detailed design of distillation, lists of equipment suppliers, terminology for membrane and membrane processes, and conversion factors.

Overall, this is a very good book. Every chemical engineer who teaches, researches, or uses these separation processes should have ready access to it. ❐

A FEED-EFFLUENT HEAT EXCHANGER/REACTOR DYNAMIC CONTROL LABORATORY EXPERIMENT

William L. Luyben
Lehigh University • Bethlehem, PA 18015

Exposing students to real process control instrumentation and to real process equipment in laboratory experiments is of great pedagogical and motivational importance. Simulations lack the feel, touch, smell, and sound of a real chemical plant. All chemical engineering undergraduate curricula should have some experimental dynamics and control component.

Most control experiments used in undergraduate laboratories are quite simple because they are intended to reinforce basic ideas and principles learned in the theory part of the course. Single-loop control of level, temperature, or pressure is typical, with conventional PID algorithms used in digital controllers. Many papers have been published over the last four decades describing several types of laboratory experiments and course objectives and approaches. Recent papers include the work of Bequette, et al.,[1] and Lennox and Brisk.[2]

While these simple processes are necessary for initial experiments, they do not expose students to processes that are more challenging and that are commonly encountered in the chemical industry. More complex experiments are of great help in improving students' understanding of process-control basics. This paper describes one such process, the feed-effluent heat exchanger/reactor system. The apparatus is fairly simple and is safe to operate, and the investment in process equipment and instrumentation is modest.

The experiment was developed as part of the Lehigh Interdisciplinary Controls Laboratory, which has been in operation for almost a decade.[3] The laboratory is an elective course for chemical, electrical, and mechanical engineering seniors. Experiments in the three disciplines are performed by interdisciplinary teams. Students perform three very basic experiments during the first half of the semester. During the last half they perform two more advanced experiments. The laboratory is operated two afternoons a week for three hours. Faculty supervision is provided by all three departments.

PROCESS DESCRIPTION

The need to preheat the feed to a tubular reactor to some minimum inlet temperature is one of the important features of tubular reactors that distinguishes them from continuous stirred-tank reactors in which a minimum feed temperature seldom exists. With a tubular reactor, if the feed temperature is too low, the reactor will "quench" (move to a low-conversion steady state). Feed preheating can be done using a steam-heated heat exchanger or a fired furnace, depending on the temperature level required. Cooling of the reactor effluent is usually required, and this can be done by steam generation or using cooling water. The use of independent utility streams for preheating and cooling makes the control problem very easy because there is no interaction (see Figure 1A).

This arrangement, however, is quite inefficient from a capital-investment and energy standpoint. Separate heating and cooling heat exchangers are required, which increases capital investment in heat-transfer area. The need to have reasonable temperature differential driving forces in both

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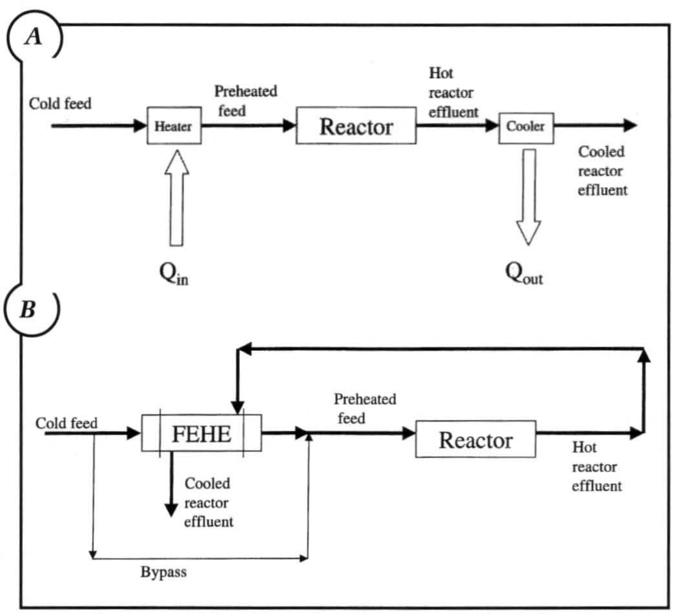

***Figure** 1A. Independent heating and cooling. 1B. FEHE Process.*

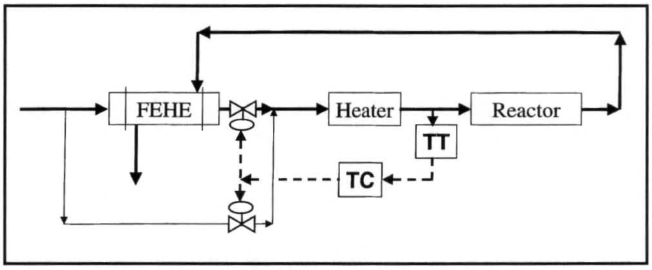

***Figure 2.** Process flowsheet.*

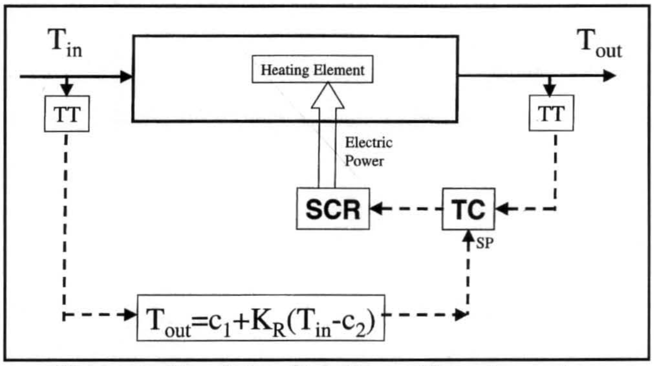

***Figure 3.** Simulate adiabatic exothermic reactor.*

heat exchangers reduces the thermodynamic efficiency of the process.

In a large number of industrial applications, the hot reactor effluent is used to preheat the cold reactor feed. The resulting decrease in heat-transfer area means lower capital investment and a more efficient process in terms of steady-state operation. Figure 1B shows a feed-effluent heat exchanger coupled with an adiabatic exothermic reactor. The heat of reaction produces a reactor effluent temperature that is higher than the temperature of the feed stream to the reactor. Therefore heat can be recovered from the hot stream leaving the reactor.

This feed-effluent heat exchanger (FEHE) configuration results in significant dynamic control problems, however. This is one of the classic examples of the interaction and conflict between design and control. The control objective is to control the reactor inlet temperature by manipulating the bypass flow of cold material around the heat exchanger.

These FEHE systems have been used for many years in the chemical and petroleum industries. Papers describing the dynamics and control issues date back almost four decades,[4,5] with several recent studies appearing in the literature.[6-10] The importance of the FEHE configuration in the chemical industry is indisputable.

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

Figure 2 gives a schematic of the experiment. Air from a 90-psig air supply flows through a pressure regulator that provides a constant pressure air source (50 psig). A manual valve sets the total air flow through the process. The pressure drop through the system is designed to be about 5 psi. Thus the pressure drop over this manual valve gives choke flow through the valve ($P_{in} > 2\ P_{out}$). This means that the flowrate is independent of the downstream pressure, so the total flow is constant for any downstream conditions.

About 25% of the air passes through the tube side of a heat exchanger in which it picks up heat. The remainder of the cold air is bypassed around the heat exchanger and mixed with the hot air leaving the heat exchanger. The split-ranged control valves in both the bypass line and the heat-exchanger exit line are positioned by a temperature controller, which controls the reactor inlet temperature. Since the safe failure mode is bypassing cold gas to the reactor, the bypass valve is air-to-close and the heat-exchanger valve is air-to-open.

The total air stream after mixing enters a heater that is used to add heat during startup and for openloop testing of the individual components of the system. Then the air stream enters the "reactor." Because of safety, environmental and cost-of-raw-material concerns, we do not use real chemicals. An exothermic adiabatic tubular reactor is simulated by using a vessel with an electric heater. The instrumentation looks at the inlet temperature and adjusts power to raise the exit temperature to the desired level. The reactor gain (*i.e.*, how much the reactor exit temperature changes for a given change in the inlet temperature) is set to simulate a typical change in a chemical reaction rate with temperature. The instrumentation to achieve this is shown in Figure 3. The gain in the computing relay can be adjusted to give the desired reactor gain. The hot gas leaving the reactor passes through the shell side of the FEHE and a rotameter and is vented to the atmosphere.

The power controllers in the heater and reactor are 110 volt SCR units driving the type of electrical heating element used in heat guns (commonly used for paint removal). They

TABLE 1
Equipment List

Item	*Description*	*Cost ($/unit)*	*No.*	*Cost*
Reactor/heater	See Fig. 9	1,100	2	2,200
Heating elements		30	2	60
Temperature indicator		450	1	450
Heat exchanger		500	1	500
Controller		700	1	700
Control valves	=%trim, 1/2" trim	400	2	800
Throttle valve		125	1	125
I/P transducers		500	2	1,000
Air supply regulator		150	1	150
4-way valves		125	3	375
Manual valves		125	3	375
Integral-orifice flow transmitter		1,400	3	4,200
Instrument air regulator		150	1	150
Recorder/Logger	multi-trend, 8 inputs	3,500	1	3,500
Panel lights and switches		100	3	300
SCR controller		2,100	2	4,200
Control console		1,800	1	1,800
Software for recorder		300	1	300
Piping and fittings				500
Computing relay	reactor gain	500	1	500
Thermocouples		35	10	350
Flow switch		100	1	100
Rotameter		350	1	350
Relief valve		50	1	50
Air filter and drier		200	1	200
Flow indicator		350	1	350
Gages		25	4	100
Temperature transmitter		1,150	1	1,150
Support frame		500	1	500
Total Equipment Cost				**$25,335**

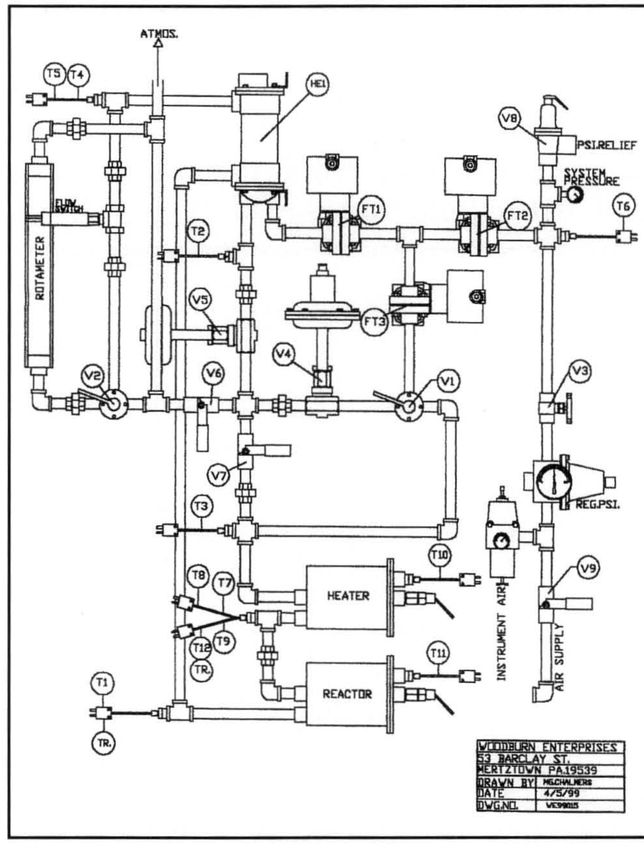

Figure 4. Equipment layout.

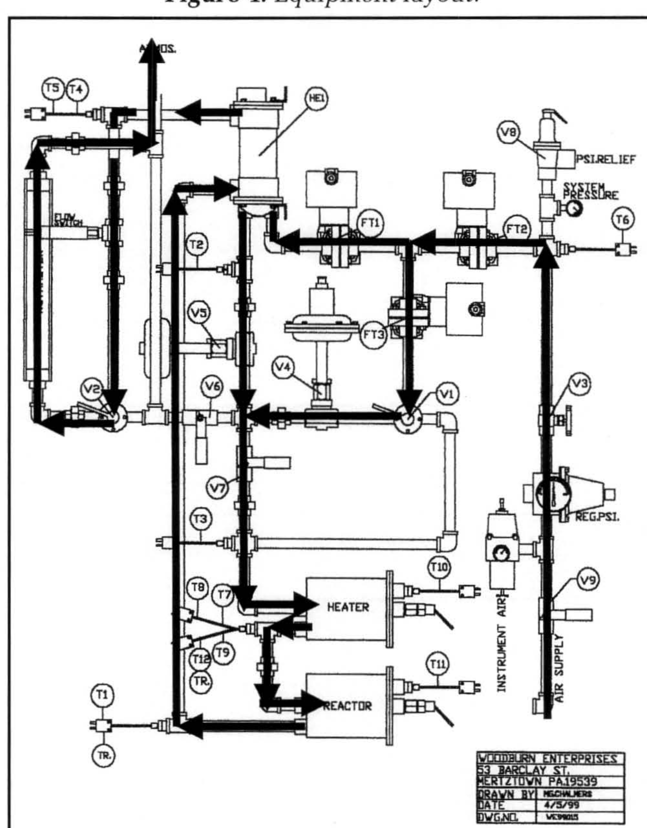

Figure 5. Normal mode.

have a power output of 600 watts. Table 1 gives a list of equipment. Iron-constantan thermocouples are used for temperature measurements at numerous locations in the process. Integral-orifice differential pressure transmitters and a rotameter are used for flowrate measurements. Figure 4 gives details of the piping and valving. Temperatures and flowrates are recorded on strip charts on the control panel and logged in a data-acquisition computer. The reactor-inlet temperature controller, the heater controller, and power switches for the heater and reactor are also located on the panel.

The piping and valving are designed to have two modes of operation:

1. *Normal mode: Air flow is as described above (see Figure 5).*
2. *Test Mode: Air flow is split between two loops as shown in Figure 6. In the first loop, air flows through the heater, reactor, and shell side of the heat exchanger and is vented. In the second loop, air flows through the tube side of the heat exchanger and is vented. Changes in the power to the heater produce changes in the temperatures in and out of the reactor and in the temperature of the air leaving the tube side of the heat exchanger. This data can be used to obtain approximate transfer functions for the reactor and for the heat exchanger.*

The split-ranged control valves are 0.5 inch with equal-percentage trim. The air-to-open valve in the heat exchanger line is biased, as shown in Figure 7, so that it is wide open when the controller output signal is at 50%. This keeps the pressure drop through the valves fairly constant for any controller output signal for a constant total flowrate of air, which is set at about 8 SCFM. To protect against damage to the heating elements, a low-flow switch cuts power to the heating elements in the heater and reactor if the air flowrate drops below 6 SCFM. This flow switch protects these elements in both the normal and test mode configurations.

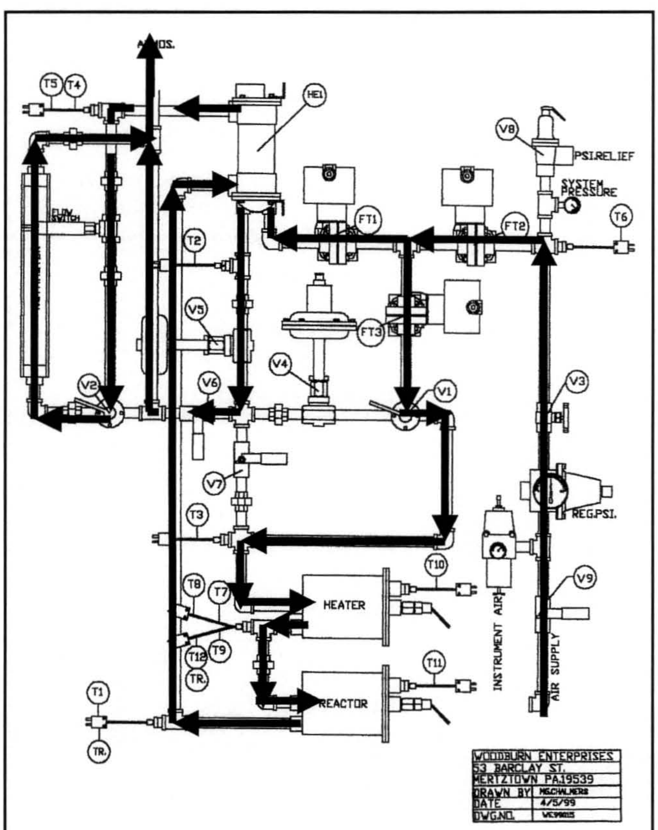

Figure 6. *Test mode.*

Typical steady-state operating temperatures are:

- inlet air, 70°F
- heat exchanger tube-side exit, 130°F
- mixed-gas, 115°F
- reactor inlet, 115°F
- reactor exit, 180°F
- heat exchanger shell-side exit, 135°F.

Heat-transfer area in the heat exchanger is 2.5 ft^2.

PROCEDURE

Openloop Experimental Data Collection

Normal Mode

1. Position the valves so the gas flow is in the normal operation configuration (Figure 5).
2. Open the supply air line and adjust valve V3 to get 8 SCFM on the rotameter. Turn on the main power
3. Calibrate the flow transmitters in the bypass and heat exchanger lines by varying the reactor inlet temperature controller output (CO) from 0% to 50% with the controller on manual. Read the total flow from the rotameter and from the total flow meter. Make plots of CO versus SCFM through each valve.

Test Mode

1. Position the valves so the gas flows can pass indepen-

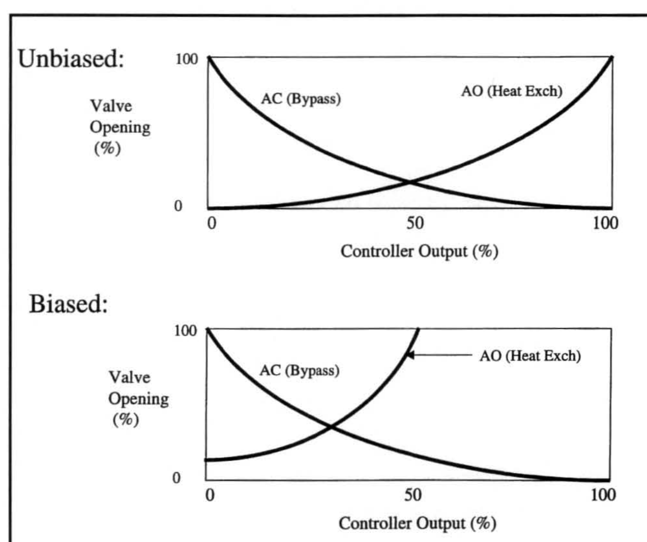

Figure 7. *Split-range control valves.*

dently through the reactor and the heat exchanger in the test mode (see Figure 6).

2. With the temperature controller in manual, adjust the controller output to 15%.
3. Turn on power to the heater and adjust the heater controller to obtain an exit temperature of about 115°F.
4. Turn on the power to the reactor. Let the process come to steady state.
5. Calculate energy balances around the heat exchanger and calculate the overall heat-transfer coefficient U.
6. Make a step change in the heater power and record the responses of the reactor inlet temperature, the reactor exit temperature, and the heat exchanger tube-side exit temperature. Use this data to calculate the openloop transfer function for the heat exchanger relating T_{HX} to T_{out} and the openloop transfer function for the reactor relating T_{in} to T_{out}.
7. Turn off the power to the heater and reactor. Wait for two minutes with air flowing to cool off the system.

Closedloop Experimental Data

1. Start up the system in the normal operating mode with heater and reactor power off. With the reactor inlet temperature controller on manual, set its output at 50%. Turn on power to the heater and to the reactor.
2. When the reactor inlet temperature reaches 95°F, turn off the heater power. Observe what happens to the reactor inlet and exit temperatures.
3. Turn the power to the heater back on. When the reactor inlet temperature reaches 120°F, turn off the heater power. Observe what happens to the reactor inlet and exit temperatures.
4. Put the reactor inlet temperature controller on automatic with $K_c = 5$ (with a temperature transmitter span of 160°F) and $\tau_I = 2$ min, and with

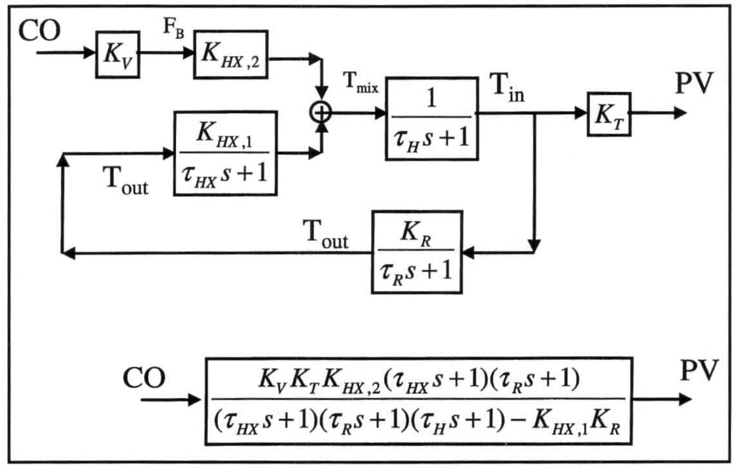

Figure 8. *Block diagrams of openloop coupled system.*

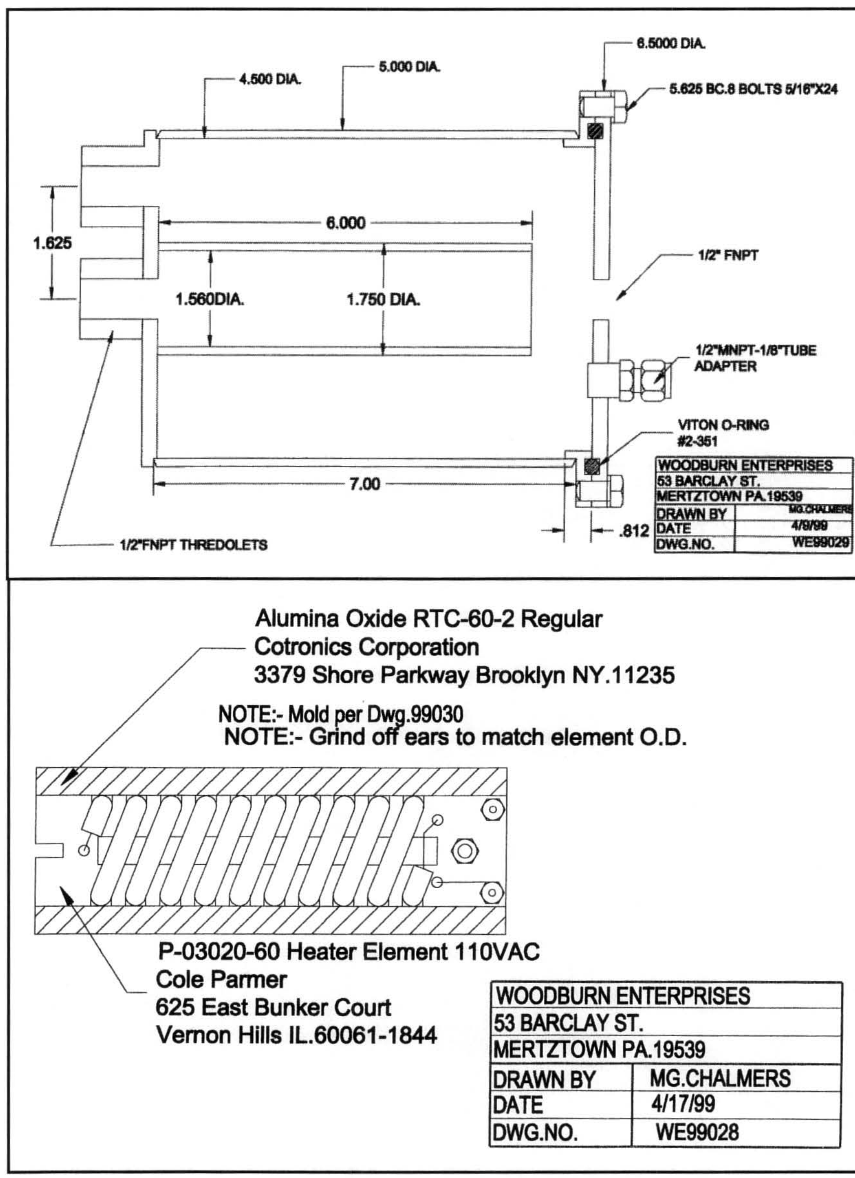

Figure 9. *Reactor/heater vessel*

a reactor inlet temperature setpoint of 115°F.

5. Record the closedloop response of the system for ±5°F changes in setpoint.

Theoretical Predictions

1. From the bypass and heat-exchanger flowrates and temperatures, calculate the steady-state gain for the transfer function relating T_{in} to the controller output signal CO.
2. Assume this transfer function consists of a gain and first-order lag. Use the same heater time constant found above.
3. Using the three experimental openloop transfer functions, predict the openloop response of the coupled system.
4. Calculate the minimum controller gain that will stabilize the coupled system.
5. Make a root locus plot and a Nyquist plot for the coupled system.
6. Make root locus plots for PI controllers with the values of $\tau_I = 1$ min and $\tau_I = 2$ min.
7. Calculate the theoretical closedloop setpoint response using the process openloop transfer functions and the PI controller transfer function. Compare the predicted response with the experimental response.

THEORETICAL ANALYSIS

Figure 8 gives a block diagram of the individual components in the openloop system. We assume that the dynamics of the hot and cold stream mixing after the heat exchanger are negligible, so the mixed-gas temperature T_{mix} is related to the flowrate of the bypass stream F_B by the algebraic equation

$$T_{mix(s)} = K_{HX,2} F_{B(s)} \tag{1}$$

Note that $K_{HX,2}$ is negative since an increase in bypass flowrate decreases T_{mix}. This means that the temperature controller $G_{c(s)}$ must increase the bypass flowrate when the temperature increases. Since the bypass valve is air-to-close, its gain is negative (increasing controller output signal CO decreases bypass flow F_B). Thus, the controller must have a positive gain (reverse acting controller).

The transfer function relating bypass flow and controller output is the valve transfer function, which we assume is just a gain, $F_B/CO = K_V$, and can be calculated from the experimental valve calibration data.

The transfer function for the temperature transmitter, which relates the controlled variable, T_{in}, to the signal to the controller PV is

$$K_T = \frac{PV}{T_{in}} = \frac{100\%}{\text{Span}°\text{F}} \tag{2}$$

The mixed-gas temperature also depends on the temperature of the hot gas leaving the reactor (T_{out}). The transfer function relating T_{mix} to T_{out} is assumed to be a gain and first-order lag

$$G_{1(s)} = \frac{T_{mix(s)}}{T_{out(s)}} = \frac{K_{HX,1}}{\tau_{HX} s + 1} \tag{3}$$

The reactor is assumed to have the simple openloop stable transfer function with a negative pole at $s = -1/\tau_R$

$$G_{R(s)} = \frac{T_{out(s)}}{T_{in(s)}} = \frac{K_R}{\tau_R s + 1} \tag{4}$$

These transfer functions can be combined, as shown in Figure 8, to give the openloop transfer function of the coupled system.

$$G_{CP(s)} = \frac{PV_{(s)}}{CO_{(s)}} = \left[\frac{K_{HX,2} K_T K_V (\tau_{HX} s+1)(\tau_R s+1)}{(\tau_{HX} s+1)(\tau_R s+1)(\tau_H s+1) - K_{HX,1} K_R}\right] \tag{5}$$

This equation shows that the coupled system is *openloop unstable* if the product of the gains $K_{HX,1}K_R$ is greater than one. The heat exchanger gain $K_{HX,1}$ depends on the heat-transfer area and the approach temperature differential on the hot end of the process (the temperature difference between the entering hot stream and the exiting cold stream), but it cannot be greater than unity. The reactor gain K_R depends on the heat of reaction, the temperature dependence of the reaction rate, and the initial extent of conversion. In the simulated reactor, this gain is set to be about four.

Root locus plots or Nyquist plots using a proportional controller ($G_c = K_c$) can be used to determine the *minimum* value of controller gain that gives a stable closedloop system.

Note that the openloop transfer function of the coupled system is net first order, *i.e.,* the numerator polynomial is second order and the denominator polynomial is third order. This means that theoretically there is no maximum gain (ultimate gain). Adding two first-order lags to account for temperature measurement and valve lags gives a third-order system, which has an ultimate gain and ultimate frequency.

$$\left[\frac{K_{HX,2} K_T K_V (\tau_{HX} s+1)(\tau_R s+1)}{(\tau_{HX} s+1)(\tau_R s+1)(\tau_H s+1) - K_{HX,1} K_R}\right] \frac{1}{(\tau_M s+1)(\tau_V s+1)} \tag{6}$$

OPERATING EXPERIENCE

The experiment was constructed in late 1998 and operated in the Interdisciplinary Controls Laboratory during the 1999

Continued on page 73.

SOME PITFALLS WITH CITATION STATISTICS

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The motivation for writing this article is to report on an experience that we in the Department of Chemical Engineering at Carnegie Mellon University had with citation statistics. We believe it is worth sharing this experience, particularly in light of the recent article by Angus, *et al.*,[1] who proposed alternative ways of measuring quality for ranking chemical engineering departments. The main idea in that article was to eliminate surveys and rely exclusively on quantitative measures, with citations being one of the major metrics. As we will describe in this article, great care has to be exercised in gathering and interpreting these data, as otherwise it is easy to obtain misleading conclusions (see Centra[2] for a general discussion on problems with citation analysis).

THE CARNEGIE MELLON CASE STUDY

In 1992, *Science Watch* [**3**(2), pp. 1-8, April 1992] published an article titled "Chemistry that Counts: The Frontrunners in Four Fields." In that article, the table on page 8 listed the following as the top six departments in citations per paper during the period of 1984-1990:

#	University	Papers 1984-90	Citations 1984-90	Citations per paper
1	Carnegie Mellon University	98	670	6.84
2	Twente University of Technology	79	490	6.20
3	University of Wisconsin, Madison	106	629	5.93
4	University of Minnesota, Minneapolis	125	697	5.58
5	University of Texas, Austin	132	732	5.55
6	Massachusetts Institute of Technology	205	1134	5.53

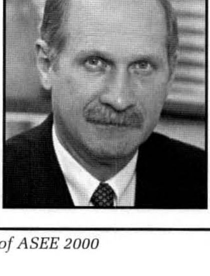
The source used in that study was 58 dedicated journals of chemical engineering (subsection of ISI Current Contents/ Engineering Technology and Applied Science).

On the other hand, according to the 1995 NRC Report, Appendix Table P (p. 500), the ranking in terms of citations per faculty for the five top U.S. departments and Carnegie Mellon for the period of 1988-92 was:

#	University	Citations 1988-92	Citations per Faculty
1	University of Minnesota, Minneapolis	3751	117.2
2	Stanford University	1039	103.9
3	University of Texas, Austin	2874	95.8
4	University of California, Berkeley	1697	89.3
5	Massachusetts Institute of Technology	2438	78.6
...			
41	Carnegie Mellon University	359	21.1

The source used was also the ISI Database and covered a considerably larger, but unspecified, number of journals.

The studies covered different periods, 1984-1990 vs. 1988-1992, as well as a different domain of journals. Nevertheless, it was clear that the number of citations reported in the NRC Report for Carnegie Mellon seemed to be much lower. In particular, the number of citations from the NRC study (359) was one-half of the *Science Watch* study (670), even though the NRC Report presumably covered a larger number of journals.



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. . . great care has to be exercised in gathering and interpreting these data, as otherwise it is easy to obtain misleading conclusions.

The above discrepancy prompted us to conduct an independent study in the summer of 1996. We received two databases from ISI containing the names and papers from our faculty in the period 1981-1995. In the first database, no biological science journals were included; in the second, they were included. The numbers that we found were as follows for the period 1988-1992 for Carnegie Mellon—we included only active faculty (17 faculty, as in NRC Report) during that period (retired or deceased faculty were excluded):

a) Without biological sciences

Total citations	1241
Citations per faculty	73

b) With biological sciences

Total citations	2747
Citations per faculty	162

The reason for the large increase in citations with biological sciences was that several papers were published by Rakesh Jain in *Cancer Research.* For instance, one of his papers[3] had a total of 265 citations for the 1981-1995 period.

So, what can we conclude from the above numbers?

Even if we were to exclude the biological science journals and remove 40% as an estimate for taking the data in 1996 rather than in 1993 (see point #3 below), the statistics are

Total citations	745
Citations per faculty	44

Therefore, compared to the NRC numbers there was at least a difference factor of two in the number of citations. In fact, if we consider the worst case (only 745 citations), Carnegie Mellon's rank would have been 14, with 44 citations per faculty. In the more realistic case of 1241 citations, our rank would have been 6, with 73 citations per faculty. In both cases, there is clearly a rather large discrepancy with the original rank of 41 for citations per faculty.

It should also be pointed out that the number of publications per faculty reported for Carnegie Mellon in Appendix K (p. 286) is significantly lower than it should be. That table reports 8.2 publications per faculty compared to 14.9 from the ISI database (*i.e.,* 254 publications and 17 faculty). Therefore, based on the count of number of publications, only about one-half were considered in the NRC Report.

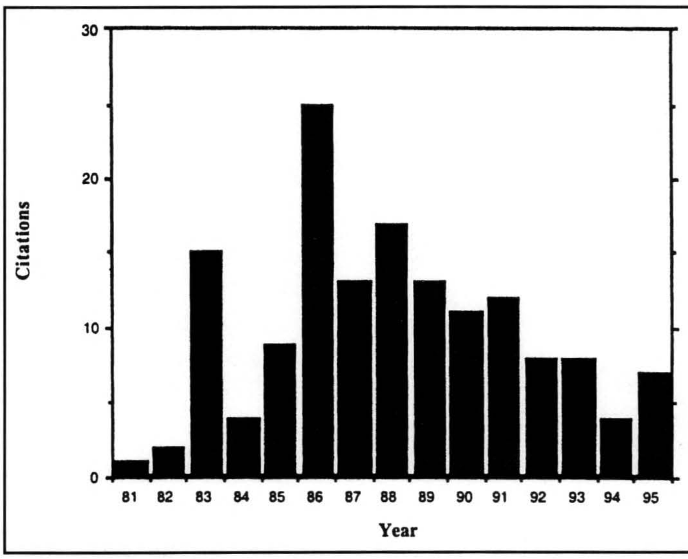

Figure 1.** Plot of citations versus time for* IEEE, ***69, *p. 1232 (1981)*

We contacted both the NRC and the ISI for clarification. Based on their input, as well as on our experience in working directly with the ISI database, we summarize below the possible pitfalls that we identified with the citation statistics.

WHAT ARE THE POTENTIAL PITFALLS?

1. Misspelling of Names of Authors

This is a rather simple, but very critical, issue that we found when requesting information from ISI. The two extreme cases are 1) common names and 2) names that are easily misspelled. For example, in our department the data we received from John L. Anderson, our current Dean of Engineering, contained a very large number of papers in other areas. We had to manually separate the entries that corresponded to our John Anderson because the database did not allow simultaneous specification of both name and affiliation.

At the other extreme, the name of the author of this manuscript, Ignacio E. Grossmann, was initially misspelled with one "n" (Grossman), and a similar difficulty occurred with Andrew Gellman (Gelman). As a consequence, we received only a handful of citations in the initial request; the ones with the misspelled last names. Missing middle initials was another problem.

2. Domain of Journals for Search

As the study in the 1992 *Science Watch* indicated, a large number of journals was excluded (compared to the NRC Report) since the study was confined to "chemical engineering" journals. The NRC, however, was also not immune to problems. We were told by its staff that only certain disciplines were associated with each journal. This clearly means that departments with faculty publishing in the nontraditional disciplines were most probably penalized.

3. *Timing of Measurement of Citations Relative to Publication Times*

In our study at Carnegie Mellon, we found the following interesting observation: Most papers that have a significant number of citations (say, greater than 50), achieve their maximum number of citations between 4 to 6 years from publication. An example of this is a paper by Arthur Westerberg[4] that had a total of 149 citations. As shown in Figure 1, the maximum number of citations in this paper was in 1986, five years after its publication. This trend held in many of our papers. The implication is clear: Statistics for papers that have been out for only 1 to 3 years will probably miss more than 75% of the citations that such a paper may receive.

4. *Interpreting the Number of Citations*

One of the most important issues when reporting the number of citations over a given time period is determining what this exactly means. Intuitively, it may appear that it is the total number of citations that were made to a given author for that time period and for papers published *prior to* and during that period. But if one uses an ISI database over a given time period, the result obtained is only the number of citations of papers published in that particular time period.

To give a specific example, consider the 1988-92 time period that was used by NRC, measured in 1993. The total number of citations would intuitively be the citations of papers published before 1988-92 and during 1988-92. But what one obtains from the ISI database is only the number of citations of those papers published *during* the period 1988-92. Therefore, according to point #3 above, for a 1988 paper we pick up five years of the life of a paper, while for a 1992 paper we pick up only one year of its life. Aside from the fact that this will be an inaccurate count that will greatly underestimate the number of citations, it will be biased toward papers that are cited earlier in their lifetime (*i.e.,* papers of immediate impact).

5. *Variations of Citations by Areas*

This is a well-known fact, but it deserves discussion. Let us consider the two papers

1 Jain, R., "Determinants of Tumor Blood-Flow: A Review," *Cancer Research* (1988)
2 Fortescue, Kershenbaum, Ydstie, "Implementation of Self-Tuning Regulators with Variable Forgetting Factors," *Automatica* (1981)

Up to 1995, paper #1 had 265 citations, while paper #2 had 195 citations. Based on point #3, we might say paper #1 may still have some way to go to increase its number of citations. Furthermore, it already has more citations than paper #2. Should we then conclude paper #1 is more successful than paper #2?

Consider the following fact: In *Cancer Research* the expected number of citations of any given paper is 163.6; in *Automatica* it is only 15.9. (According to the ISI, the expected number of citations is the number of citations from papers of that journal, divided by the number of papers in that year.) If we divide the number of citations by the expected number of citations in the journal, one might argue that paper #2 is ten times more successful!

Finally, a related issue in citation statistics is the "impact score" of each journal, which often greatly varies by research area and largely has to do with the size of its audience. The impact score is calculated by dividing the number of citations in the past two years by the number of articles published during the same period. Statistics reported (URL: http://fellini.sissa.it/~furio/journal.html) in 1996 for some journals where chemical engineers publish are

1.359	*AIChE Journal*
1.056	*Industrial & Engineering Chemistry Research*
0.902	*Chemical Engineering Science*
0.532	*Canadian Journal of Chemical Engineering*
0.488	*Chemical Engineering Research & Design*
0.385	*Chemical Engineering Communications*
25.466	*Nature*
22.067	*Science*
22.524	*Pharmacological Reviews*
12.48	*Journal of Cell Biology*
7.507	*Journal of Clinical Oncology*
1.228	*Physics Letters A*
3.056	*Physics Letters B*
6.626	*Physical Review Letters*
3.635	*Journal of Chemical Physics*
2.492	*Journal of Catalysis*
2.745	*Surface Science*
1.864	*Journal of Fluid Mechanics*
3.016	*Macromolecules*
3.232	*Langmuir*
1.401	*Colloids and Surfaces*
1.62	*Journal of Colloid and Interface Science*
2.603	*Environmental Science & Technology*
0.9	*Automatica*
0.641	*Computers & Chemical Engineering*
0.864	*Mathematics of Operations Research*
0.763	*Mathematical Programming*
0.729	*Operations Research*
0.356	*European Journal of Operational Research*

Based on the above, it is clear that the impact factors are quite uneven in different areas. Furthermore, it is interesting to note that the *Journal of Fluid Mechanics* and *Mathematical Programming,* two journals that are notoriously difficult for accepting papers, have rather low impact factors compared to *Nature* and *Science*, which are also very selective. These observations would suggest the need for some type of normalization; *e.g.,* 30 citations of an article in the *Journal of Fluid Mechanics* could be considered a success, while 30 in *Nature* would correspond to an average paper in that journal.

CONCLUDING REMARKS

This article has demonstrated, using the experience at Carnegie Mellon with statistics on the numbers of citations, that there are a number of important potential pitfalls in compiling that type of information due to the great complexity in gathering and interpreting the information. Our experience with *Science Watch* and the NRC Report suggest that there is a pressing need for organizations that perform department rankings to carefully and rationally define measures of citations in order to avoid errors, misinterpretations, and biases against certain research areas. While we do not attempt to offer specific remedies, it would seem that the following five general policies merit consideration:

1. *Develop an identification number for authors to avoid problems with misspellings and duplicate names.*
2. *Expand the domain of search to all areas to avoid penalizing authors who publish outside of their discipline.*
3. *Consider normalizing citations according to the impact score, to reduce discrepancies between different research areas.*
4. *Ensure that the number of citations over a given time period cover publications before and during that time period.*
5. *Consult with departments to verify the statistics before publishing them, to allow for possible corrections of mistakes.*

In order to implement these policies, close collaboration with ISI and agencies performing the rankings is required. It is also hoped that this article will temper the enthusiasm of those who apply sophisticated analysis tools to questionable data, and thereby are likely to draw incorrect conclusions.

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ChE letter to the editor

Dear Editor

Alves, et al.,[1] are to be congratulated on their elegant experiment on the drainage of liquids from vertical tubes of diameter 19 and 32 mm. But their paper should have stipulated that the diameter of tube used should be no less than about 15 mm. The reason is that the simple equation for the bubble velocity

$$U = 0.345(gD)^{0.5} \tag{1}$$

does not apply for smaller tubes because of surface tension effects. The relevant dimensionless group for such effects is the Eötvos number, which is given by

$$Eo = gD^2 \Delta\rho / \sigma \tag{2}$$

where D = tube internal diameter, $\Delta\rho$ = density difference between heavy and light phases, and σ = surface or interfacial tension.

At values of Eo less than about 50 in the case of low-viscosity liquids, the velocity U is below the value predicted from Eq. (1). Moreover, if Eo is below a critical value of 3.37, corresponding to a tube diameter of about 5 mm for air/water, the bubble will not rise at all.[2] Some years ago we measured drainage rates from vertical tubes of between 6 and 10 mm diameter, with the bubble nose (meniscus) being controlled at a constant position.[3] This technique enabled the surface tension in gas-liquid and liquid-liquid systems to be measured continuously.

M.H.I Baird, *Professor*
N.V. Rama Rao, *Research Associate*
McMaster University

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Random Thoughts . . .

ALL IN A DAY'S WORK

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It's a typical day in your class. As you lecture,

- *several students stroll in during the first 10 minutes of the class and one arrives after 20 minutes. It is the earliest she has arrived all semester.*
- *a number of students are absorbed in the campus newspaper.*
- *two students are having an animated conversation, punctuated by laughter. All heads around them are turning to see what's going on.*
- *one student has his head back, eyes closed, and mouth open.*

You are not thrilled by all this, but you're not sure what to do about it.

We sometimes present this scenario in our teaching workshops and ask the participants to brainstorm possible responses to any of these behaviors—not just good responses, but good, questionable, and terrible responses. Here are typical suggestions.

1. Ignore it.
2. Lock the door.
3. "YOU TWO SHUT UP!"
4. Fall silent and wait.
5. Throw chalk.
6. Set off a firecracker.
7. Flap your arms and cluck like a chicken.
8. Ask a question.
9. Leave.
10. Set fire to the newspaper.
11. Talk to the offender outside class.
12. Review the rules.
13. Start an activity.
14. Throw the bums out.
15. "That looks like an interesting conversation over there—why don't you share it with the rest of us?"

Next, we suggest that the *best* response depends on whether the offending behavior is disruptive or non-disruptive—that is, whether or not it distracts the class's attention from your teaching—and whether it is a first offense or a recurring one. Non-disruptive behaviors include sleeping (without snoring), reading, or slipping into the back of the room late. You may not like it—seeing students asleep drives some instructors crazy—but it is not distracting to the other students. (Watching someone sleeping just doesn't have that much entertainment value.) Disruptive behaviors include talking or otherwise making noise, or coming in late and promenading ostentatiously up the aisle.

After making these distinctions between different offending behaviors, we tell the participants to get into groups of three or four and try to reach consensus on the best response for each category. We collect their nominations and then propose ours. Sometimes several groups nominate our responses; often none do.

You might enjoy making your own nominations before we tell you ours. In your opinion, what is the best way to deal with

(a) *a student sleeping in class whom you have never seen sleeping before?*

(b) *a student who sleeps in almost every class session?*

(c) *two students talking and laughing who have not done so before?*

(d) *two students talking and laughing who do so frequently?*

First indicate what you would do in class when you ob-

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__Rebecca Brent__ is an education consultant specializing in faculty development for effective university teaching, classroom and computer-based simulations in teacher education, and K-12 staff development in language arts and classroom management. She co-directs the SUCCEED Coalition faculty development program and has published articles on a variety of topics including writing in undergraduate courses, cooperative learning, public school reform, and effective university teaching.

serve the offensive behavior, and then add what (if anything) you would do outside class. *Hint*: One of our nominations is not included in the 15 listed ones.

Best response to non-disruptive behavior

If you do *anything* in class to address a non-disruptive behavior, you turn it into a disruptive one. Our suggestion for what to do in class about a sleeping (or reading or unobtrusively late) student is, therefore...*nothing*. If the student is a first-time offender, forget about it. If you notice the same student sleeping every period, you may continue to ignore it, or if it seriously annoys you, you might express your annoyance outside class and ask why he is doing it. If he is bored, knowing that his sleeping bothers you may get him to work harder at staying awake. On the other hand, if he is holding down a 40-50 hour/week job while going to school or is working the night shift, warn him that he could be missing important information and then stop worrying about it.

Sometimes someone suggests initiating a learning activity to get students' attention. We are staunch believers in active learning, but we want to use activities when they fit, not just because we happen to see someone sleeping.

Best response to disruptive behavior

Ignoring disruptive behavior is not a viable option. If you allow disruptions to proceed, they will become increasingly widespread and frequent until the class is out of control.

Our nomination of the best response requires some preliminary explanation.* Speech communication experts tell us that there are three categories of responses to objectionable behavior: *aggressive, passive (indirect)*, and *assertive.* Yelling at students, throwing things at them, and throwing them out of class are aggressive responses. Doing anything non-aggressive other than clearly stating what you want is a passive response. Calmly and clearly stating the problem and asking for what you want is an assertive response.

Do aggressive responses work? In the short run, they generally do. As an instructor, you hold a great deal of power over the students: if you scream at them to shut up, chances are they will. But while you may win the battle, you are likely to lose the war. When you resort to aggression, you effectively admit that the only way you can control your class is to lose control of yourself. You will lose the respect of the students, and the rest of the semester could be grim for both you and them.

What about throwing the chalk or an eraser? Everyone has stories—some fond, some bitter—about teachers they had or knew about who used to do that sort of thing. That was then; this is now. Can you say "law suit"?

Then there are passive responses. Ignoring those two chattering students—the ultimate passive response—is clearly a poor idea. Falling silent and waiting for them and other noisemakers to quiet down themselves might work eventually, but it wastes valuable class time (especially in a large class, where you might wait for a *long* time) and penalizes the non-disruptive students as much as the few miscreants. Locking the door penalizes chronic latecomers, but it also penalizes the one-time offender who may have a perfectly legitimate and unavoidable reason for being late.

Some professors argue for the ever-popular "Why don't you share that joke with the rest of us?" That is, first of all, a passive response. You are not asking for what you really want: the last thing in the world you want is to know what those two birds are twittering about. You know, and they know, and the rest of the class knows, that your goal is simply to embarrass them into quieting down. Will it work? Again, probably in the short term, but once you resort to sarcasm or anything else that has embarrassment as its objective you again lose respect that may be hard or impossible to regain.

Which brings us to our nomination: the direct, assertive response. Look in the direction of the offending students and calmly say "Excuse me—that noise is disrupting the class. Could you please keep it down?" They usually will. The talkers may be mildly embarrassed but your primary objective was clearly not to embarrass them—it was simply to quiet them down. You maintain control without having to use aggression or sarcasm, and the students' respect for your authority stays the same or increases.

Finally, what if you have to quiet down the same students in several classes, or the same student keeps coming in late? We propose doing the same thing we suggested for repeated non-disruptive behaviors. Talk to the offenders outside class, telling them that their behavior is offensive and must stop, and then ask them why they're doing it. Regardless of what they say, you will probably achieve your objective. In our combined years of teaching, we have never had to do this with a student more than once. Barring pathological cases, neither should you.

Interestingly, the assertive response—simply asking the offenders to stop doing what they're doing—is usually not on the list of possibilities brought up during the initial brainstorm. It's almost as if instructors don't know it's legal to do it. It is legal. And it works. ❐

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* *We are indebted to Rebecca Leonard of the N.C. State University Department of Communication for the analysis that follows.*

All of the *Random Thoughts* columns are now available on the World Wide Web at
http://www2.ncsu.edu/effective_teaching/ and at http://che.ufl.edu/cee/

The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and that elucidate difficult concepts. Manuscripts should not exceed ten double-spaced pages if possible and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

APPLICATION OF A HEAT PUMP
A Feasibility Study

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Distillation is one of the most widely used separation processes in the chemical and allied industries. Among possible distillation schemes with energy saving, incorporation of a heat pump can be very efficient—but any decision in a particular distillation problem should be very carefully considered. First and foremost, a separation process must be feasible; *i.e.,* it must have the potential of giving desired results. The decision of whether to use a heat pump or not depends on the economics of the process. An established practice is to make a preliminary design or feasibility study to decide whether to proceed with detailed calculations.

Before digital computers, the economic design of multicomponent fractionating towers and other vapor-liquid contacting devices was a tedious, difficult, and time-consuming job. Various "short-cut" methods were developed to simplify the task of designing multicomponent columns, and those methods are still useful in preliminary design work, where they can greatly reduce the number of calculations to be made. With the advent of large-capacity, high-speed digital computers and sophisticated calculation techniques, however, many new and powerful programs for process design have been developed.[1] One of them is ChemCAD III,[2] —a powerful and comprehensive chemical-plant simulation program.

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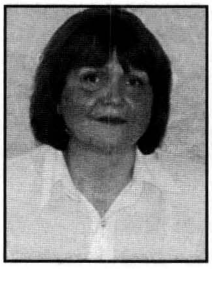
THEORY

The initial design includes a prelimary flow diagram, material and energy balances, determination of the equipment size, and estimation of equipment costs and utility energy.

The preliminary flow diagram shows the arrangement of basic individual units of equipment. The flowsheet commands of ChemCAD III allow for a very simple creation of the flowsheet. The flowsheet menu has two basic purposes:

1. *To define the flowsheet; i.e., the unit operations and their connectivity*



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2. *To establish the calculation order of the flowsheet simulation*

The full simulation program is capable of carrying out rigorous simultaneous heat and material balances and preliminary equipment design. Our example will describe the techniques for solving multicomponent distillation problems of an interconnected flowsheet.

Distillation with Vapor Recompression

Three arrangements of heat pumps are possible.[3-5] In each case, compression work is normally used to overcome the adverse temperature difference, which precludes having the condenser serve as the heat source for the reboiler in an ordinary distillation column. If conditions are suitable, the process fluid can be used as the working fluid for the heat pump. In alternative arrangements, the process vapor is taken from the top of the column, compressed, and fed to the reboiler to provide heating. In distillation systems where the heat pump is applicable,[4] the heat pump with direct overhead vapor recompression proves to be the most economic solution. The compressor is the "heart" of the system. The ratio of compression is crucial to the power requirements, and depends on

$$\Delta p_{com} = \Delta p_{col} + \Delta p_b + \Delta p_c + \Delta p_{eq} \tag{1}$$

Relations between pressures and temperatures are given on the p/T diagram shown in Figure 1.

The ratio of compression is

$$r = \frac{p_2}{p_1} = \frac{(p_t + \Delta p_{com})}{p_t} \tag{2}$$

A vapor compression heat pump applied to a distillation column is shown in Figure 2.

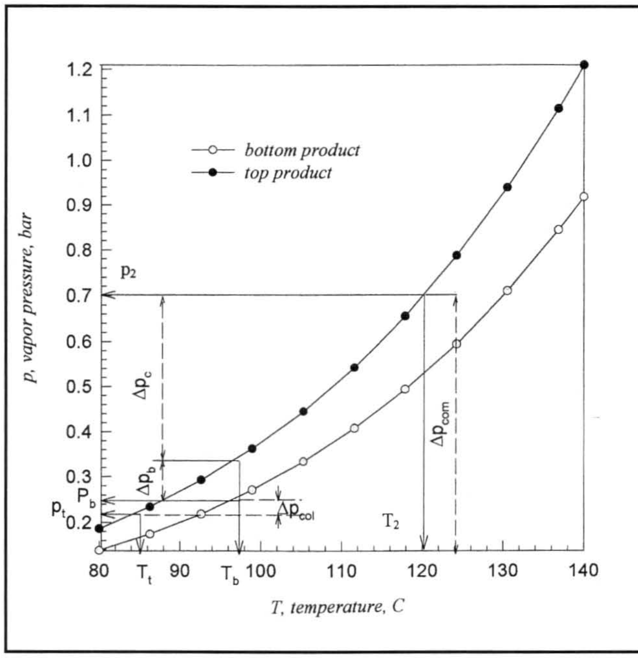

Figure 1. *Diagram of p/T for overhead vapor recompression.*

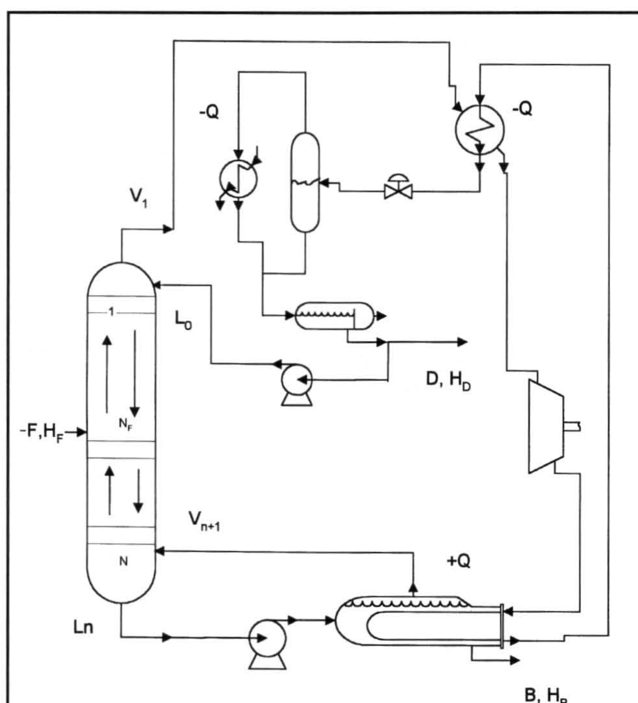

Figure 2. *Distillation column with heat pump.*

ESTIMATION OF PURCHASED EQUIPMENT COSTS

Capital cost estimates for chemical process plants are often based on the purchased cost of the major equipment items required for the process, the other costs being estimated as factors of the equipment cost. Costs are correlated against sizes of individual units. The relationship between size and cost is given by Eqs. 3 through 14.[6,8] The equipment-sizing facility inside ChemCAD III can be found under the command describing each equipment type. The following correlations for the base cost in carbon steel are given in SI units and US dollars.

Pressure vessels

$$C_{pv} = C_{pv}^0 F_m F_p \frac{I}{336.2} \tag{3}$$

$$C_{pv}^0 = (a + bL)d^{1.1} \tag{4}$$

In the following two correlations, column cost represents the sum of the costs of the shell and internals, either trays or packing.

$$C_{co} = C_{pv.vert} + C_{pack} \quad (5)$$

$$C_{pack} = C^0_{pack} d^n V_{pack} \frac{I}{336.2} \quad (6)$$

Heat Exchangers

$$C_{exc} = C^0_{exc} F_p F_{tex} \frac{I}{336.2} \quad (7)$$

$$C^0_{exc} = \exp(a + b\,\ell nA) \quad (8)$$

Pumps

$$C_{pu} = C^0_{pu} F_m F_p \frac{I}{418.3} \quad (9)$$

$$C^0_{pu} = \exp\{a + \ell n P[b + \ell n P(c + d\,\ell n P)]\} \quad (10)$$

Compressors

$$C_{com} = C^0_{com} F_m \frac{I}{418.3} \quad (11)$$

$$C^0_{com} = \exp(a + b\,\ell n P) \quad (12)$$

$$C_{em} = C^0_{em} F_{tem} F_{na} \frac{I}{331.2} \quad (13)$$

$$C^0_{em} = \exp\{5.33 + \ell n P[0.3 + \ell n P(0.162 - 0.014\,\ell n P)]\} \quad (14)$$

ESTIMATION OF UTILITY ENERGY

The word "utilities" is generally used for the ancillary services needed in the operation of any production process.[8] The services in this example include electricity, steam for process heating, and cooling water. The quantities required can be obtained from the energy balances and the flowsheets. The prices will depend on the primary energy sources and the plant location.

Cooling water

Mass flow rate of water

$$Q_{mass(H_2O_{liq})} = \frac{Q_{HD}}{C_p \Delta T} \quad (15)$$

Price of cooling water: \$0.02/m³

$$\text{Cost} = 0.02 \frac{Q_{mass(H_2O_{liq})}}{\rho_{water}}$$

Steam

Mass flow rate:

$$Q_{mass(H_2Og)} = \frac{Q_{TD}}{Hp} \quad (16)$$

Price of steam: \$10/t

$$\text{Cost} = 10\,Q_{mass}$$

Electric power

$$\text{Cost} = \$0.07 / \text{kWh}$$

All costs of utilities are based on one year or 8,000 hours. The base date for utilities energy is the start of 1987.[3]

PROCESS PROJECT

A flow rate of 22,000 kg/h of liquid has the composition shown in Table 1. The mixture has to be distilled to give an overhead product with 0.15 mole percent styrene and a bottom product with 0.3 mole percent ethyl benzene. The necessary information for using the ChemCAD III program includes working pressures and temperatures along the column and preliminary material balances. The column will operate at a pressure of 0.23 bar at the top and a temperature of 97 °C at the bottom. The pressure drop along the column is 0.02 bar.

TABLE 1
Feed Composition

	mol%
Benzene	0.8
Toluene	1.2
Ethyl benzene	40.0
Styrene	58.0

The preliminary flow diagram and preliminary material balances are shown in Figure 3 and Table 2. Figure 3 shows a standard column configuration, *i.e.*, conventional distillation that was modified to use a heat pump with the stream transfer modules (STM). These modules serve as an abstract block in the flowsheet, and their output stream is exactly the same as their input stream.

RESULTS

The feed rate is 22,000 kg/h. The mean molecular weight

TABLE 2
Preliminary Material Balance

	Feed		*Top*		*Bottom*	
Comp	*kmol/h*	*fraction*	*kmol/h*	*fraction*	*kmol/h*	*fraction*
Benzene	1.680	0.008	1.680	0.019	0	0
Toluene	2.520	0.012	2.520	0.029	0	0
Etbenzene	84.000	0.400	83.750	0.950	0.250	0.002
Styrene	121.800	0.580	0.190	0.002	121.610	0.980
Total	**210.000**	**1.000**	**88.140**	**1.000**	**121.860**	**1.000**

of the liquid mixture is

$$M = \sum x_i M_i = 0.008 \times 78.114 + 0.012 \times 92.141 + 0.40 \times 106.168 + 0.58 \times 104.52 = 104.61$$

Thus, the molar flow rate of feed is 22,000/104.61 = 210.3 kmol/h.

EQUIPMENT SIZES OBTAINED BY CHEM CAD III SIMULATION

▶ *Distillation Column*

- Type and size of packing: Intalox ceramic saddle (3 inch)
- Height required for the specified separation: 86 m
- Column diameter (capacity): 7.5 m

▶ *Distillation Storage Tank*

	Conventional Distillation	*Heat Pump*
Height (width), m	*8.23*	*8.23*
Diameter, m	*2.74*	*2.74*

▶ *Vapor-Liquid Separator*

	Heat Pump
Height (width), m	*13.26*
Diameter, m	*4.42*

▶ *Heat Exchanger: Heat duty and area*

	Conventional Distillation	*Heat Pump*
Heat duty Q, kJ/h (E01, E05)	-1.4×10^8	-1.74×10^7
Heat duty Q, kJ/h (E02, E04)	1.4×10^8	3.73×10^6
Heat duty Q, kJ/h (E03)	-	1.41×10^8
Area, m² (E01, E05)	*213.0*	*165.1*
Area, m² (E02, E04)	*690.2*	*261.4*
Area, m² (E03)	-	*5,549.0*

▶ *Pumps: Pumping power*

	Conventional Distillation	*Heat Pump*
Power, kW (P01, P03)	*100.7*	*2.5*
Power, kW (P02, P04)	*1.9*	*1.9*

▶ *Compressor*

Compressor power: P=4,205 kW

EQUIPMENT COSTS

▶ *Conventional Distillation: Purchased equipment cost*

Equipment Items		*Price: $*
Tower	*T01*	*$2,315,000*
Pump	*P01*	*15,470*
Pump	*P02*	*760*
Vessel	*D01*	*25,660*
Condenser	*E01*	*39,440*
Reboiler	*E02*	*140,000*
	Total	***$2,536.330***

▶ *Utilities Cost*

Utilities	*Cost: $/year*
Steam	*$4,467,200*
Cooling water	*1,457,600*
Electrical power	*62,400*
Total	***$5,987,200***

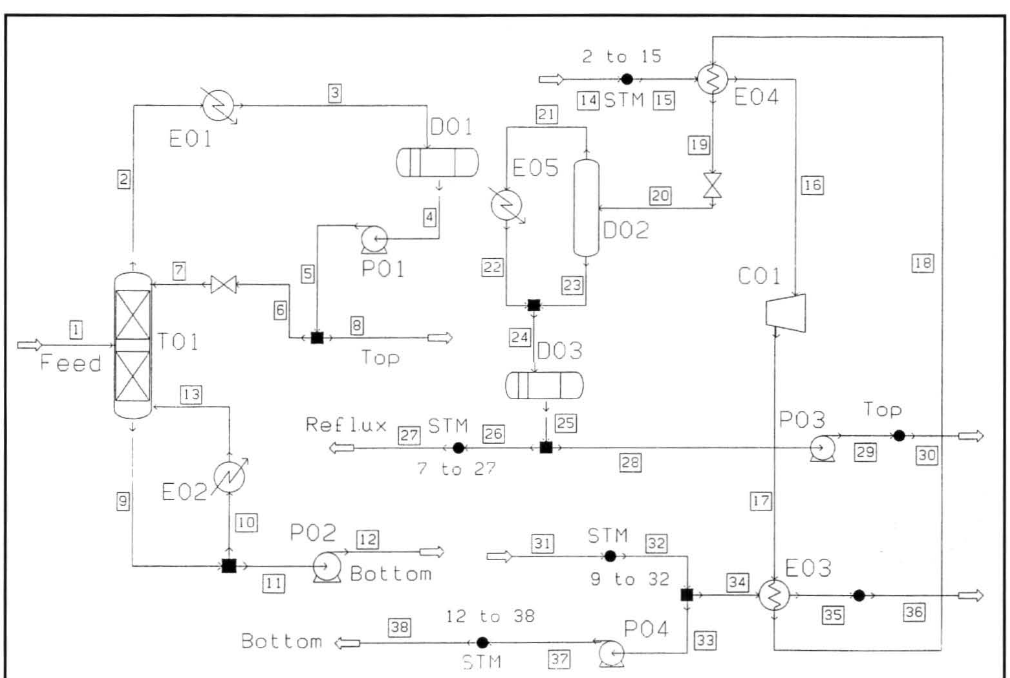

Figure 3. Process flow diagram

► *Distillation with Heat Pump: Purchased Equipment Cost*

Equipment Items		*Price: $*
Tower	*T01*	*$2,315,000*
Pump	*P03*	*3,360*
Pump	*P04*	*770*
Condenser	*E04*	*45,090*
Condenser	*E05*	*33,210*
Heater	*E03*	*334,750*
Compressor	*C01*	*3,683,000*
Separator	*D02*	*68,000*
Storage tank	*D03*	*25,670*
	Total	***$6,508,850***

► *Utilities Cost*

Utilities	*Cost: $/year*
Cooling water	*182,400*
Electrical power	*2,572,000*
Total	***$2,754,400***

► *Summary of Annual Costs*

	Conventional Distillation: $/year	*Heat Pump:$/year*
Equipment (amortized over ten years)	*$253,630*	*$650,890*
Utilities	*$5,987,200*	*$2,754,400*
Total	***$6,240,830***	***$3,405,290***

CONCLUSION

The purpose of this example is not to obtain a detailed calculation, but to illustrate the methodology of a preliminary design of equipment and obtain a feasibility study. The preliminary design includes shortcuts in calculations so that the cost estimates of equipment probably contain moderate errors. There are two alternative designs for the distillation and the aim of this work is to find which of them is more attractive economically. Both designs are feasible.

The results show that the application of the heat pump with vapor recompression is more economically justified. The purchased cost of the major equipment items required for the process with the heat pump is 2.5 times higher than for conventional distillation, but the energy costs saved easily justifies the investment after one year's operation of the equipment.

The above example shows the benefits of making a preliminary calculation to prove whether or not to proceed with detailed calculations.

NOMENCLATURE

a,b,c,d, coefficients in Eqs. (4) and (8)
A heat transfer area, m^2
C_{co} cost of column, $
C_{com} cost of compressor, $
C^0_{com} base cost of compressor, $
C_{em} cost of electromotor, $
C^0_{em} base cost of electromotor, $
C_{exc} cost of exchanger, $
C^0_{exc} base cost of exchanger, $
C_{pack} cost of packing per unit volume, $/$m^3$
C^0_{pack} base cost of packing per unit volume, $/$m^3$
C_{pu} cost of pump, $
C^0_{pu} base cost of pump, $
C_{pv} cost of pressure vessel, $
$C_{pv,vert}$ cost of vertical vessel, $
C^0_{pv} base cost of pressure vessel, $
d diameter, m
Δp_b vapor pressure difference between overhead and bottom product at column bottom temperature, bar
Δp_c pressure difference between hot and cold side in evaporator/condenser, bar
Δp_{col} column pressure drop, bar
Δp_{eq} equipment and pipes pressure drop, bar
Δp_{com} growth pressure in compressor, bar
F_m material cost factor
F_{na} electromotor purpose cost factor
F_p pressure cost factor
F_{tem} electromotor type cost factor
F_{tex} exchanger type cost factor
I inflation index
L length of column, m
P power, kWh
p_1 compressor suction pressure, bar
p_2 compressor discharge pressure, bar
p_b column bottom pressure, bar
p_t column top pressure, bar
Q heat transferred per unit time, kJ/h
Qv flowrate, m^3/h
r compression ratio
U overall heat transfer coefficient, kJ/m^2K
V_{pack} volume of packing, m^3
ΔTm mean temperature difference, the temperature driving force, K
η_p pump efficiency

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Laboratory Experiment

Continued from page 61.

spring semester. Four groups of students ran the experiment. Each group was in the laboratory collecting data during three consecutive three-hour laboratory periods (a week and a half). The theoretical analysis took about a week. Reports were due at the end of the third week.

The initial experimental temperature data was inconsistent and unreliable due to transmitter and recorder calibration problems. We also had to reduce the size of the control valves and change the trim from linear to equal percentage. Once these hardware bugs were worked out, the students were able to collect and analyze good data. Energy balance revealed significant heat losses because of the small scale of the equipment. Additional insulation was added.

Although the digital data logger is convenient for storing data for later plotting and for making calculations, an old-fashioned multichannel analog strip-chart paper recorder made it much easier to follow the dynamic transients as they occurred.

The response of the students was quite positive. They found the experiment both challenging and educational. The chemical engineering students were particularly interested in this experiment because many of them were working in their design course on dynamic simulations of chemical processes that featured reactor/heat-exchanger systems.

INTERESTING FEATURES

The coupled system is openloop unstable, but whether the temperature increases or decreases depends on the initial conditions. At low-temperature initial conditions, temperature drops exponentially. At high-temperature initial conditions, temperature increases exponentially. This is what should occur in Steps 2 and 3 of the Closedloop Experimental Data Procedure. The mechanical equivalent of this phenomenon is the trajectory of an inverted pendulum; it can fall to either one side or the other, depending on the initial position and velocity.

Runs with different reactor gains can be made to illustrate how this parameter affects the rate of the openloop runaway (or quench) and how it affects controller tuning.

Another modification is to run with different heat exchanger areas. This can be achieved by having two heat exchangers in series (on both the tube and shell sides) that can be valved in or out of the system.

ACKNOWLEDGMENT

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NOMENCLATURE

F_B flowrate through bypass
G_C controller transfer function
G_{CP} openloop transfer function of coupled system
G_H heater openloop transfer function relating T_{in} to T_{mix}
$G_{HX,1}$ heat exchanger transfer function relating T_{out} to T_{in}
$G_{HX,2}$ heat exchanger transfer function relating T_{out} to F_B
G_R reactor openloop transfer function relating T_{in} to T_{out}
K_c controller gain
K_H gain of heater openloop transfer function relating T_{in} to T_{mix}
$K_{HX,1}$ gain of heat exchanger transfer function relating T_{out} to T_{in}
$K_{HX,2}$ gain of heat exchanger transfer function relating T_{out} to F_B
K_R gain of reactor openloop transfer function relating T_{in} to T_{out}
K_u ultimate gain
τ_H time constant of heater openloop transfer function relating T_{in} to T_{mix} [min]
$\tau_{HX,1}$ time constant of heat exchanger transfer function relating T_{out} to T_{in} [min]
$\tau_{HX,2}$ time constant of heat exchanger transfer function relating T_{out} to F_B [min]
τ_R time constant of reactor openloop transfer function relating T_{in} to T_{out} [min]
τ_I controller reset time [min]

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VAPOR-LIQUID EQUILIBRIA IN THE UNDERGRADUATE LABORATORY

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Separation and purification processes account for 70 to 90% of equipment and energy costs in modern chemical plants,[1] with distillation being among the most expensive.[2] Moreover, phase equilibrium measurements and thermodynamic modeling are key elements of chemical process design, and it is therefore not surprising that vapor-liquid equilibria (VLE) receives heavy emphasis in the undergraduate chemical engineering curriculum. Students typically learn the fundamentals of VLE and other phase equilibria as part of their thermodynamics course work, but many programs rely on a VLE laboratory exercise to reinforce and extend the knowledge gained in the classroom.

The classical undergraduate experiment involves measuring the VLE behavior of a binary mixture, often by direct compositional measurement at constant temperature and pressure. This requires charging a still with the binary system of interest and allowing the system to equilibrate, after which one records the temperature and pressure inside the still and obtains samples of both phases for compositional analysis. Common analytical techniques (*e.g.*, gas chromatography and refractive index) are time-consuming, allowing acquisition of just a few data points during a typical laboratory session and precluding a meaningful data reduction. Students therefore miss an opportunity to practice the thermodynamic modeling skills that are crucial to process design.

In a recent paper, Campbell and Bhethanabotla addressed the pitfalls of using direct compositional analysis in the undergraduate laboratory and recommended the total-pressure method as an alternative approach to acquiring VLE data.[3] This method, in which students record pressure isothermally as a function of (known) liquid composition over a wide composition range, eliminates the need for compositional analysis. Instead, vapor phase compositions are calculated by employing a suitable activity coefficient model in accordance with the method of Barker.[4] A counterpart of the total pressure method is to record isobarically the boiling temperature for multiple liquid compositions, an approach that has been in use at the University of Delaware for many years.

An important issue in any undergraduate laboratory exercise is the effective use of limited time, and time is certainly a key consideration in the industrial practice of thermodynamics where project deadlines dictate a need for the rapid acquisition of accurate VLE data.[5] Although the total-pressure method is adequate in this regard, we found that significant improvements are possible via the method of infinite dilution, isobaric ebulliometry. This method allows acquisition of data points every fifteen minutes and can be used with a modest number of data points near the compositional limits.

Given a set of four ebulliometers, groups of three students are able to measure the infinite dilution VLE behavior of two binary systems during a single laboratory session. If the two binary systems share a common component, then students can model the VLE behavior of a ternary system by combin-

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ing their experimental results with data for a third binary mixture taken from the literature. This paper describes the implementation of infinite dilution ebulliometry in the undergraduate laboratory and its application to ternary VLE.

METHODOLOGY

Ebulliometry allows measurement of VLE by the principle of liquid-phase and vapor-condensate recirculation, and Cottrell was the first to use an ebulliometer for undergraduate instruction (in 1910).[2] The Cottrell design, which used a thermal lift pump, was later modified by Swietoslawski. Although alternative designs abound, the original Swietoslawski design remains the standard in ebulliometry (for a review, see Hala[6]).

Ebulliometers operate exceptionally well with dilute solutions and allow accurate determination of infinite dilution activity coefficients, γ_i^∞. The practical definition, in our VLE context, of an infinitely dilute solution is a mixture for which the temperature changes linearly with mole fraction, and the limits of infinite dilution are specific to a given mixture. Typical limits for infinite dilution range from less than a fraction of a mole percent to several mole percent. Thus, infinite dilution ebulliometry refers to the isobaric measurement of VLE temperatures in a narrow composition range near the limit of infinite dilution rather than over a wide composition range. Working near infinite dilution limits the number of data points necessary, and the use of small aliquots avoids the need to drain and refill systems, thus conserving time.

The isobaric, infinite dilution technique involves boiling a pure liquid (solvent) of known weight and adding a very small (typically less than 0.5 mole percent), weighed amount of a second fluid (solute). The addition of solute alters the boiling point, and one records the new boiling temperature at a fixed pressure after the system reaches equilibrium. By recording the equilibrium boiling temperatures at constant pressure for several successive aliquots of solute, one obtains the dependence of boiling temperature on solute mole fraction within and slightly beyond the limit of infinite dilution. This information is sufficient to calculate activity coefficients at infinite dilution according to

$$\gamma_{\text{solute}}^\infty = \frac{P_{\text{solvent}}^{\text{vap}} - \left(\dfrac{dP_{\text{solvent}}^{\text{vap}}}{dT}\right)\left(\dfrac{\partial T}{\partial x_{\text{solute}}}\right)_{P,x_{\text{solute}}\to 0}}{P_{\text{solute}}^{\text{vap}}} \tag{1}$$

where $\gamma_{\text{solute}}^\infty$ is an activity coefficient at infinite dilution, P is the total pressure, P^{vap} is the vapor pressure, T is the absolute temperature, and x is mole fraction, where subscripts denote a given component. All qualities involving the vapor pressure are evaluated at the pure solvent boiling temperature using a readily available vapor pressure correlation (*e.g.*, Antoine, Reidel, or Harlecher-Braun)[7] The information obtained from the ebulliometric experiment is merely the limiting value of the partial derivative

$$\left(\partial T / \partial x_{\text{solute}}\right)_{P,x_{\text{solute}}\to 0}$$

and computation of the liquid phase activity coefficients at infinite dilution from Eq. (1) is straightforward.

Activity coefficients at infinite dilution become useful when one considers the criteria for VLE, namely the equality of component fugacities among phases at uniform temperature and pressure. It is customary to represent the liquid phase fugacity with an activity coefficient (as opposed to an equation of state) so that under conditions of low total pressure the equilibrium criterion for any component, i, becomes

$$x_i\gamma_i(T,P,x_i)P_i^{\text{vap}}(T) = y_iP \tag{2}$$

where x_i and y_i denote liquid- and vapor-phase mole fractions, respectively, γ_i is the liquid-phase activity coefficient, $P_i^{\text{vap}}(T)$ is the pure-component vapor pressure, and P is the total-system pressure. Pressure remains constant, the liquid-phase mole fraction is calculated by a mass balance, and vapor pressures are calculated in the manner described above. The only unknowns in Eq. (2) are the activity coefficient and the vapor-phase mole fraction. When activity coefficients are known, one can easily calculate the composition of the equilibrium vapor phase; the challenge is to evaluate the activity coefficients.

Most activity coefficient models (*e.g.*, Wilson, van Laar, two-constant Margules) for binary systems contain two system-dependent parameters, the values of which are generally unavailable. As an example, the binary van Laar model may be written

$$\begin{aligned} \ell n\ \gamma_1 &= A_{12}\left(\frac{A_{21}x_2}{A_{12}x_1 + A_{21}x_2}\right)^2 \\ \ell n\ \gamma_2 &= A_{21}\left(\frac{A_{12}x_1}{A_{12}x_1 + A_{21}x_2}\right) \end{aligned} \tag{3}$$

where subscripts 1 and 2 denote the two binary components and the parameters A_{12} and A_{21} are unknown. Under conditions of infinite dilution, Eq. (3) simplifies to

$$\begin{aligned} \ell n\ \gamma_1^\infty &= A_{12} \\ \ell n\ \gamma_2^\infty &= A_{21} \end{aligned} \tag{4}$$

where γ_i^∞ is the activity coefficient of component i when component i is present as the (infinitely dilute) solute. Thus, the infinite-dilution technique provides a means of estimating the two model parameters, A_{12} and A_{21}, which can then be used to calculate activity coefficients and the equilibrium vapor-phase mole fraction for any liquid composition. This technique can be implemented rapidly, and the values of γ_i^∞

determined experimentally lead to fairly reasonable predictions of VLE over the entire range of binary compositions.[8] Azeotropic temperatures may be slightly over- or underestimated, but generally the composition of an azeotrope, if present, is well targeted.

Moreover, the technique allows estimates of ternary VLE when the procedure is applied to two additional binary systems with a common component. A second mixture, made of components 1 and 3, leads to the binary van Laar activity coefficient parameters A_{13} and A_{31}. Similarly, a third mixture comprising components 2 and 3 gives the binary van Laar activity coefficient parameters A_{23} and A_{32}. The six binary parameters enable calculation of activity coefficients in a ternary system comprising components 1, 2, and 3 according to the ternary van Laar model[9]

$$\ell n\gamma_1 = \frac{\left\{x_2^2 A_{12}\left(\frac{A_{21}}{A_{12}}\right)^2 + x_3^2 A_{13}\left(\frac{A_{31}}{A_{13}}\right)^2 + x_2 x_3 \frac{A_{21}A_{31}}{A_{12}A_{13}}\left(A_{12}+A_{13}-A_{23}\frac{A_{12}}{A_{21}}\right)\right\}}{\left[x_1 + x_2\left(\frac{A_{21}}{A_{12}}\right)+x_3\left(\frac{A_{31}}{A_{13}}\right)\right]^2} \quad (5)$$

A similar expression for $\ell n\gamma_2$ is obtained by interchanging subscripts 1 and 2 in Eq. (5) and for $\ell n\gamma_3$ by interchanging subscripts 1 and 3.

EXPERIMENTAL APPARATUS

Our undergraduate VLE laboratory is equipped with four ebulliometers to allow simultaneous measurement of four activity coefficients (*i.e.,* two binary mixtures). Ideally, six ebulliometers would be used for studying the ternary system, but preserving the division of labor among three students during a single laboratory session (*i.e.,* 3-4 hours) dictates a practical limit of four ebulliometers. The ebulliometers were constructed to our specifications by A.A. Pesce, Inc., and are a slight modification of the original Swietoslawski design.[6] Figure 1 shows the primary components of the ebulliometers: the boiler (A), the Cottrell pump (B), the thermowell (C), and the condenser (D).

Each ebulliometer is packed with fiberglass insulation, secured in a wooden housing, and mounted on a steel frame. The network of ebulliometers, which is set on casters for ease of transport, is positioned beneath a central fume hood for ventilation (see Figure 2). The boilers are supplied separately by four circulating hot-water baths (Fisher Scientific model 9101), and each thermowell is equipped with a platinum RTD (Omega model PR-13-2-100-1/8-12-E) and digital display (Omega model DP41-RTD). The circulating baths are controllable to within 0.1°C, and the precision of the RTDs is 0.01°C. The condensers are supplied by a central cooling system that consists of a 15-gallon polyethylene tank (Nalgene model 14100) and a centrifugal pump (Cole-Parmer model 7021). The cooling medium is an ice/water bath that is maintained at about 2°C. Ambient pressure is measured to a resolution of ±0.1 mm Hg with a centrally located mercury barometer.

Operation of the ebulliometer involves charging a known mass of solvent (~60 mL) to the boiler, which can be accomplished by simply pouring the solvent from a tared beaker. The solvent is then heated to its boiling point via the circulating hot water bath. When boiling commences, rising vapors within the Cottrell arms entrain small droplets of liquid so that a two-phase flow impinges upon the thermowell. The liquid phase falls under the influence of gravity, whereas the vapors continue to rise into the condenser. Condensed vapors flow to the bottom of the thermowell, where they mix with the descending liquid phase, and all liquid returns to the boiler.

An important point to make with students is that by its very nature the

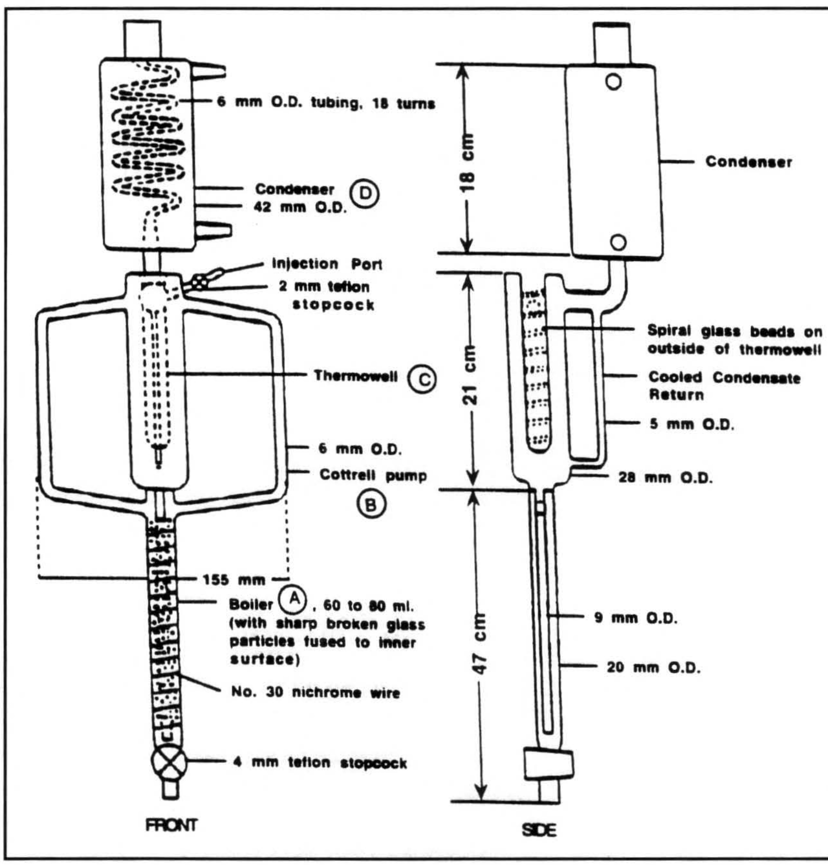

Figure 1. *Schematic diagram of a modified Swietoslawski ebulliometer.*

ebulliometric experiment represents a steady-state process when stabilized. The intimate contacting of vapor and liquid in the Cottrell pumps, however, assures achievement of local equilibrium; boiling temperatures of pure solvents measured with the ebulliometer agree to within 0.05°C of the accepted equilibrium values.

When steady state is reached, a small aliquot (100-1000 μL) of solute is added via a gas-tight syringe through an injection port on the thermowell. This method for loading solute is necessary to avoid errors in weighing, since the solute mass must be known to within ±0.005 g to obtain values of $\left(\partial T / \partial x_{solute}\right)_{P, x_{solute} \to 0}$ with less than 1% error. This is less of a concern for the solvent mass, which requires a precision nominally one-hundred fold less than that of the solute. A new steady state is reached shortly after injecting, and the new steady-state temperature is recorded on a plot of temperature versus (liquid phase) solute mole fraction. This process is repeated until the steady-state temperature profile becomes nonlinear, indicating that the range of infinite dilution has been exceeded.

MATERIALS

Students are assigned one ternary system to be modeled on the basis of the three associated binary systems. The students are required to obtain the two activity coefficients at infinite dilution (one for each component) for each of two of the binary systems. They obtain infinite dilution activity coefficients for the third binary system from the Dechema Data Series, and we encourage students to obtain the original references cited therein.[10] Moreover, we require that students familiarize themselves with the Material Safety Data Sheets (MSDS) for each chemical that they will be using and to understand the implications of the information when performing the experiment. A wide variety of solvents can be selected, but we typically choose a combination of binary pairs that includes at least one azeotrope. Table 1 is a listing of the ternary solvent systems used in recent years at the University of Delaware. Note that several of these reagents, in particular methanol and chloroform, require careful consideration in view of safety issues associated with handling.

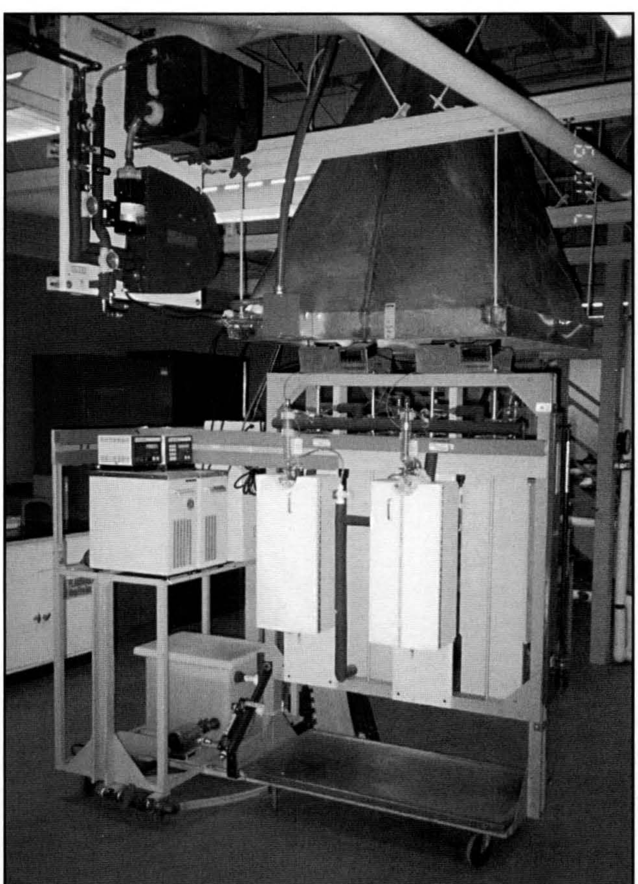

Figure 2. *Experimental apparatus used in the undergraduate laboratory for VLE studies.*

SAMPLE EXPERIMENT

To illustrate the infinite dilution technique, we refer to an experiment from the Spring 1997 semester in which students modeled the behavior of the ternary system acetone-methyl acetate-methanol. Students made measurements on the binary systems acetone-methanol and methyl acetate-methanol, and results for the acetone-methanol binary will be shown. The raw data obtained from a single ebulliometer are provided in Figure 3. Temperature was measured continuously as a func-

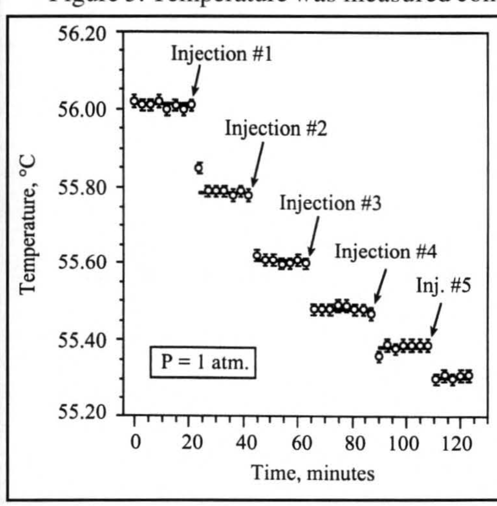

Figure 3. *Raw data obtained from the isobaric experiment. The boiling temperature in an ebulliometer filled with acetone is recorded as a function of time as aliquots of solute methanol are added. Arrows indicate the times at which aliquots were injected, and horizontal bars denote the ensuing steady-state temperatures.*

Table 1
Solvent Systems Used in Ternary VLE Experiments

1997	Acetone	Methyl Acetate	Methanol[11]
1997	Acetone	Methanol[11]	Chloroform
1996	Isopropanol	Cyclohexane	Ethyl Acetate
1996	t-Butanol	Acetone	Hexane
1995	Ethanol	Methyl Ethyl Ketone	2-Propanol
1995	Ethanol	Acetone	Ethyl Acetate

tion of time, and values were recorded every three minutes. Arrows in the figure denote solute injections, and plateaus in the profile of temperature versus time indicate the ensuing steady states. Under these conditions the temperature at the thermowell is taken to be that of the equilibrium state as discussed earlier.

A more useful form of the results in Figure 3 is a plot of equilibrium boiling temperature versus solute mole fraction, and this is depicted in Figure 4. The plot exhibits curvature as cumulative injections begin to exceed the limit of infinite dilution. Fitting the data with a 2nd-order polynomial, the initial slope gives the desired result $(\partial T / \partial x_{MeOH})_{P,x_{MeOH}\to 0}$, which is used to compute the infinite dilution activity coefficient, γ^{∞}_{MeOH}. The value of $\gamma^{\infty}_{MeOH} = 1.8$ was obtained using the three-constant Antoine vapor pressure correlation and leads to a value for the van Laar activity coefficient parameter of $A_{12} = 0.59$.

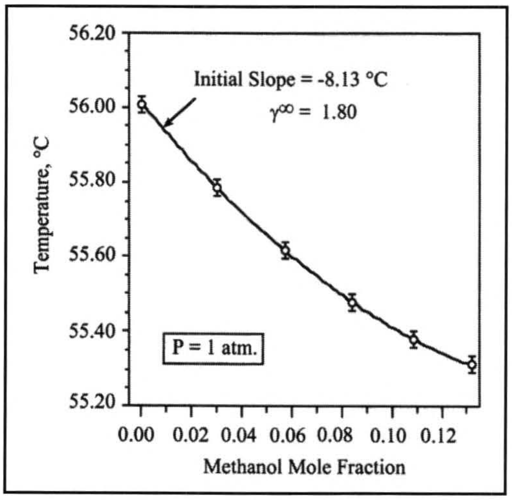

Figure 4. *Determination of infinite dilution activity coefficients. Steady-state temperatures from Figure 3 are plotted as a function of methanol liquid mole fraction. The initial slope is used to compute the infinite dilution activity coefficient for methanol via Eq. (4).*

Constructing plots similar to Figures 3 and 4, in which acetone is the solute, provides all the information necessary to estimate the full VLE behavior for the acetone-methanol binary pair. Students use that information to perform bubble-point calculations and generate a T-x-y diagram (Figure 5). The lines in Figure 5 show the acetone-methanol VLE behavior as predicted by the van Laar activity coefficient model when using the experimentally determined values of A_{12} and A_{21}. The highlight of Figure 5 is the identification of an azeotrope at a methanol mole fraction of 0.22, and students recognize the negative impact this will have on distillation. Although the partial VLE data obtained from the infinite dilution experiment are sufficient to estimate the entire VLE behavior, there is no guarantee that the predicted VLE is correct. Inaccuracies could stem from the infinite dilution measurements or from the choice of activity coefficient model that may not be suitable for the combination of solvents being studied. Students separate these effects by first comparing experimental data with accepted literature values within the range of infinite dilution. This allows a check of the ebulliometric technique itself in that it provides an estimate of the errors in the slopes $(\partial T / \partial x_{solute})_{P,x_{solute}\to 0}$ that are used to predict the VLE at intermediate compositions.

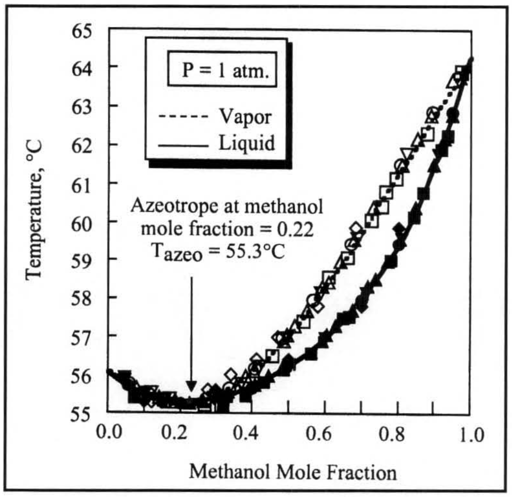

Figure 5. *T-x-y diagram showing the VLE behavior for the acetone-methanol binary system. Lines represent predictions of the van Laar activity coefficient model, based on results from the infinite dilution ebulliometric experiment. Symbols denote literature data taken from the DECHEMA series[9] (open=vapor, filled=liquid). The minimum reveals an azeotrope at a methanol mole fraction of 0.22 and a boiling temperature of 55.3°C.*

Students then test model suitability by calculating the complete VLE behavior using a variety of activity coefficient models. We require students to compare the predictive capabilities of models that assume random mixtures (*e.g.,* two-constant Margules or van Laar) with at least one model that accounts for local compositional correlations due to differences in solute-solute, solvent-solvent, and solute-solvent interactions and hence assumes non-random mixtures (*e.g.,* Wilson, NRTL, and TK-Wilson[12]). Note that the NRTL model requires a third parameter (*i.e.,* the pre-factor, A), which cannot be determined from this experiment but which tends to fall in the range 0.2<A<0.3. The symbols in Figure 5 denote the acetone-methanol VLE behavior as determined by various authors, and students are required to compare

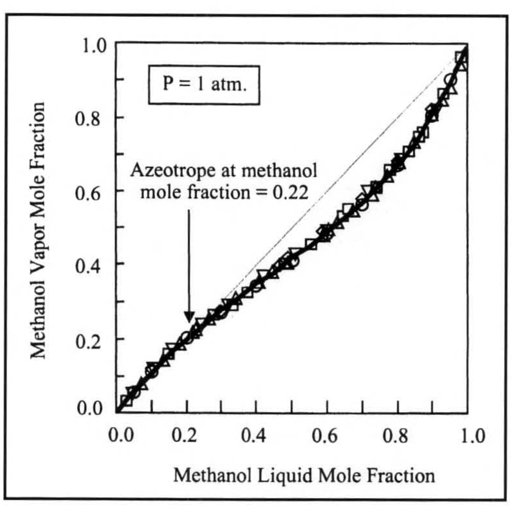

Figure 6. *x,y diagram showing the VLE behavior of the acetone-methanol binary system. Predictions from the ebulliometric experiment, using the van Laar model, are shown as a solid line. Symbols represent literature data (same as in Figure 5). The presence of an azeotrope is indicated by intersection with the 45° line.*

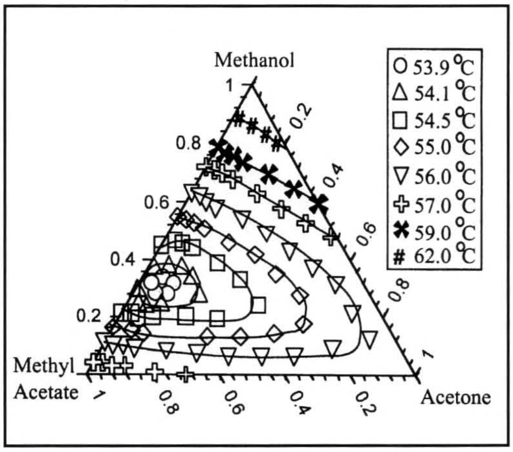

Figure 7. *Isotherms in the ternary system acetone-methyl acetate-methanol. Contours of constant temperature are plotted as a function of liquid-phase mole fractions. The isotherms converge in a "bulls-eye" fashion to reveal a ternary azeotrope at a composition of 6 mole% acetone, 62 mole% methyl acetate, and 32 mole% methanol. The azeotrope is minimum boiling at a temperature of 53.9°C.*

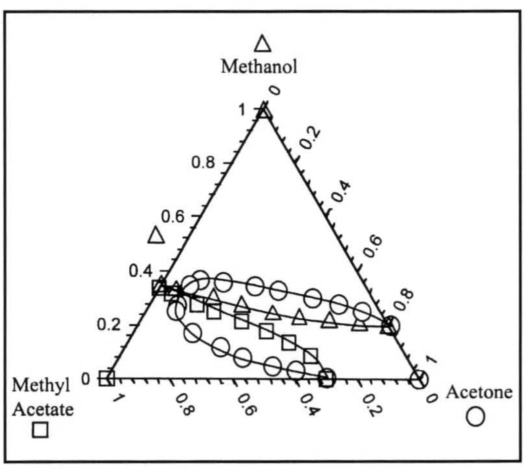

Figure 8. *Contours of K_i=1 in the ternary system acetone-methyl acetate-methanol. Contours of the partition coefficient, K_i, are plotted for each component in the case where each partition coefficient is one. Thus, the mole fraction of any component is the same in both phases along the contour for that component. The intersection of two contours, along the edge in which the mole fraction of the third component is zero, represents a binary azeotropic composition. The intersection of all three contours indicates the presence of a ternary azeotrope at a composition of 7 mole% acetone, 61 mole% methyl acetate, and 32 mole% methanol.*

the predictions of each activity coefficient model with the literature studies. Any variation in the goodness-of-fit between models, as compared with both the infinite dilution data obtained by the students and the literature data at intermediate compositions, requires students to consider which model best captures the physical differences (*e.g.,* size or polarity) between solvent and solute molecules.

Another way in which students check their results with literature studies is in the form of an x,y diagram (see Figure 6), identical to those used to construct McCabe-Thiele diagrams when sizing distillation columns. Lines again represent model predictions, and symbols denote literature studies. It is pleasing that the azeotrope obtained in Figure 6 matches that of Figure 5 as it should, but it is not uncommon (although it is not the case here) for predicted azeotropes to agree more favorably with literature compositions than with temperatures. Over the years we have found that the ebulliometric method leads to azeotropes that are nearly always correct in composition, but not necessarily correct in temperature, and this is true regardless of which activity coefficient model is used.

We attribute the above phenomenon to the presence of systematic errors that affect measurements in all four ebulliometers to nearly the same extent. This implies that variations in performance among the individual ebulliometers are not the dominant source of systematic errors. Thus, the slopes that are measured at infinite dilution for a given binary system are either both greater than or both less than the accepted values, and the magnitudes of the deviations are similar. Seldom is the case in which the error of one slope is positive and the other negative, which would of course skew the predicted azeotrope composition. This is yet another way in which students distinguish between errors in the measurements and model suitability.

Having analyzed the experimental errors and model validity in this way, students must then decide if the predicted VLE behavior is acceptable or if a complete VLE study is warranted. Thus, students learn to weigh the need for accuracy against limited resources, a lesson that will serve them well in industry.

TERNARY SYSTEM

The culmination of experimental and modeling efforts is the generation of ternary-phase diagrams. Using the four binary activity coefficient parameters they determined experimentally, in addition to two taken from the literature, students perform ternary bubble-point calculations with an activity coefficient model of their choice to create plots like those in Figures 7 and 8. Both are triangular diagrams, in which each apex denotes a pure component, and any point within the triangle represents a particular liquid-phase composition.

The series of points in Figure 7 correspond to various isotherms, and the "bulls-eye" pattern indicates the presence of a ternary azeotrope. In this case the azeotrope occurs at a composition of 6% acetone, 62% methyl acetate, and 32% methanol (all mole %) and boils at 53.9°C. This azeotrope is therefore minimum boiling, although it is possible to obtain maximum boiling and saddle-point azeotropes with other ternary systems, or no azeotrope at all.

Identification of azeotropes is a key factor when considering distillation, and students address the feasibility of separation by plotting contours of constant K_i for each component, where K_i (the distribution coefficient) is

Continued on page85

AN INTRODUCTORY ChE LABORATORY INCORPORATING EC 2000 CRITERIA

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In developing a laboratory course sequence for chemical engineering undergraduates, it is necessary to define overall course objectives as well as objectives for individual experiments. This would correspond to defining the overall course objectives and the objectives of each lecture for a traditional lecture-based course. In the past four years in this journal alone, over twenty articles[1-23] have appeared describing new and innovative individual experiments. But objectives of the course as a whole and how they are to be defined have received less attention.[24-29]

The new ABET EC 2000[30] explicitly requires that engineering departments develop in their students "the ability to design and conduct experiments as well as analyze and interpret data." Additionally, these same students must be able to "function on multidisciplinary teams," and "communicate effectively." It is incumbent on the department to document that the students have these abilities. A logical place to explicitly incorporate the development of these skills into an undergraduate curriculum is within the laboratory sequence. Here, we can not only develop the statistical experimentation and communication skills, but we can also document the progress of students in these critical areas. In addition, we can use a continuous feedback loop to revise and improve the experiments as we receive input from our alumni, advisory boards, and recruiters concerning the effectiveness and suitability of the courses for the employability of our students.

With consensus from our department's Industrial Advisory Board, we undertook a comprehensive review of our entire laboratory sequence almost two years ago. This review identified that our students needed to improve their understanding of the abstract concepts of experimental design and data analysis and be given more opportunities to practice these skills in the laboratory. Therefore, we developed a four-course sequence: one lecture course (which was new to the curriculum) and three laboratory courses (which were in the curriculum but were extensively modified) of increasing complexity, that integrated experimentation with statistical concepts and engineering science and design. These courses are summarized below:

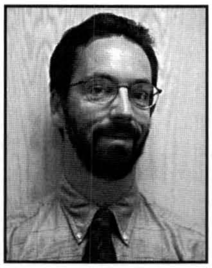
Chemical Engineering Data Analysis *A 3-credit, second-semester Sophomore course covering the theoretical aspects of experimental design and data analysis.*

Process Instrumentation Laboratory *A 2-credit, first-semester Junior laboratory introducing the students to measurement techniques, statistical analysis of engineering data, report writing, and oral presentations in small teams.*

Transport Operations Laboratory *A 2-credit, second-semester Junior laboratory in thermodynamics and heat, mass, and momentum transport where teams of students measure transport coefficients using statistically designed experiments and report their results both in writing and orally.*

Unit Operations Laboratory *A 2-credit, first-semester Senior laboratory where small teams of students characterize the performance of several unit operations and use their results in solving design problems. Written and oral reports are required.*

In this paper, the Process Instrumentation Laboratory, which was completely redesigned with new experiments, data analysis, and reporting requirements, is described in detail. By carefully selecting and designing the experiments and the organization of the course, it was possible to have the stu-



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dents meet several course objectives, including

- Conducting engineering experiments using varied experimental designs
- Analyzing experimental data using several statistical techniques
- Using different measurement methods
- Exposing the students to a variety of engineering phenomena
- Developing the student's written and oral presentation skills

COURSE ORGANIZATION

The course met for 3 hours twice each week for 16 weeks. The first four weeks were spent in 1-hour lectures reviewing statistical design of experiments and data analysis. Also included in this introductory section were lectures on laboratory safety, right-to-know training, laboratory notebook keeping, report preparation, and oral presentations.

The final twelve weeks covered the actual experimentation, analysis, reporting, and presentation phase of the course. This phase was divided into three blocks of four weeks. For each block, the students were divided into teams of 3-4 students, and each team conducted three experiments. At the conclusion of the first two experiments, the students submitted individual memorandum reports (a 2-3 page report suitable for submission to a technical manager, plus 5-10 pages of attachments documenting the procedure and data analysis and answering questions specific to the experiment). One member of each team also gave a five-minute oral presentation. At the conclusion of the third experiment in each block, the team submitted a formal report and the students who had not done an oral report did individual poster presentations of their results. New teams were formed at the beginning of each block with the same procedure for experimentation and reporting. Thus, each student submitted six memorandum and three formal reports and conducted two oral and one poster presentation during the semester.

In this paper, the Process Instrumentation Laboratory, which was completely redesigned with new experiments, data analysis, and reporting requirements, is described in detail.

Several additional aspects of the course organization are worth mentioning:

- Two days prior to each experiment (typically after the oral reports), the students were given an hour in the laboratory to review the experimental set-up.
- Each experiment had to be conducted in the allotted time (3 hours); any group not finished within that time received a zero grade for the experiment.
- Reports were graded for both technical content and for composition, grammar, readability, and conciseness. The faculty instructor was responsible for the technical content while a professional technical writer evaluated writing-related issues.
- Instant feedback was provided for the oral reports by both the class and the instructor. The presenter's group members were required to identify at least one thing about the presentation they thought was excellent and one that needed improvement. The instructor and the other students provided additional comments to the presenter as soon as the presentation was finished. This allowed all students to hear positive comments as well as areas for improvement on 9-12 presentations in a single afternoon.
- During the poster sessions, faculty and visiting industrial scientists and engineers were invited to review the posters and quiz the presenters about their work. Feedback was given immediately to the students concerning their presentation as well as their poster design.

STUDENT BACKGROUND

The students enrolled in this course typically had completed

- Engineering Data Analysis and Experimental Design
- Mass and Energy Balances
- Transport Operations I: Fluid Flow
- Chemical Engineering Thermodynamics I: Engineering Thermodynamics
- Differential Equations
- Freshman Chemistry
- Freshman Composition

In addition, the students had completed, as part of Freshman chemistry courses, the equivalent of a 2-credit general chemistry laboratory course, so they had not yet covered the engineering science background for many of the experiments. Thus, in the descriptions of the experiments and the data analysis, it was necessary to either provide the missing information (*i.e.,* the theoretical description) or to provide the appropriate references.

LABORATORY EXPERIMENTS

The experiments for the laboratory were selected and designed with the following objectives:

- Each experiment had to be completed in the allotted time (3 hours)
- Each experiment had to produce a sufficient number of data points (depending on the design, this required between 8 and 30 points per experiment) to allow statistical analysis to justify conclusions drawn by the students.
- Each experimental design (which included fractional factorials, Graeco-Latin squares, blocking, nested, and mixtures designs) should be used at least twice during the semester.
- The experimental conditions had to be easily changed so no two groups performed exactly the same experiment.
- Different fields of engineering science were to be explored.

- Some of the experiments had to explore topics that had not been covered extensively by their prior classroom experience as preparation for lifelong learning.
- For some of the experiments, the students were required to rely only on the statistical analysis of the data to develop their conclusions because of a lack of an engineering science description of the phenomena. But when a suitable engineering science description was available, the students were required to statistically validate the mathematical expressions using their data.
- When applicable, students were required to use ASTM standards.

In addition, there were the following constraints:

- Minimal use of hazardous or dangerous chemicals.
- Minimal cost of the individual experiments and, where possible, use of existing facilities and instrumentation.

A short description of each of the nine experiments can be found in Table 1. The balance of design and topics provided good coverage of the topics and designs within the constraints of the experiments (see Table 2).

REACTIONS AND COMMENTS FROM STUDENTS

The most common reaction from students was that the most difficult portion of the course was analysis of their data. At the beginning of the semester, most of the students viewed data analysis as a cookbook task that could be done with little thought. Throughout the semester, the students repeatedly asked what the answer should be and how they should get it. Only toward the end of the semester did most students begin to realize that data analysis was a process of discovery and that their data would have to lead them to the answer. Of course, the consensus was that this was much more difficult and time consuming than they had planned and that waiting until the last moment to conduct the analysis ensured that they would not finish in time.

TABLE 1
Descriptions of Experiments

Specific gravity of aqueous solutions • The specific gravity of mixtures of water, salt, and sugar were measured using a hydrometer. Since the maximum solubility of both solids was about 5% by weight, the simplex-centroid mixtures design was constrained to $0.95 \leq x_{water} \leq 1.00$, where x_{water} is the mass fraction of water in the solution. The data anlaysis required the students to develop a statistically significant polynomial expression for the specific gravity and plot contours of constant specific gravity on triangular graph paper. By changing the solutes, the experimental factor space can be altered, which changes the data analysis.

Heat transfer from fins • The effects of four factors on the convective heat transfer coefficient from fins were determined by measuring the end-face temperature on 16 different fins of various geometry and materials, as dictated by a 4x4 Graeco-Latin square design. A nonlinear least-squares analysis allowed the students to determine the best-fit convective heat transfer coefficients for the top and side of the fins. The end temperatures calculated with these coefficients were compared to those measured to determine if any of the factors affected the difference between the measured and calculated temperatures, *i.e,* the students were required to statistically validate the underlying engineering science. To alter this experiment, we have changed the bath temperature and could use a fan to change the convective heat transfer coefficient.

Efflux time from a baffled tank • Various baffle configurations were added to a gravity-drained tank to study their effect on drain time. Length and diameter of the exit pipe were also varied as dictated by a 3x3 Graeco-Latin square design. A simple ANOVA was used to determine the factors that significantly affected the efflux time. By changing the variable assignment in the design, a different experiment results.

Absorption by activated carbon • Blue food coloring was absorbed from aqueous solutions of various strengths by a commercial activated carbon. Factors examined in the 2^{5-1} fraction factorial design included amount of solution, concentration of food coloring in solution, the contact time, the ratio of carbon to solution, and the mixing speed. ANOVA was used to determine the significant factors. Many factors can be changed in this experiment, *e.g.*, type of carbon or colorant, temperature of the solution, etc., to create different experiments.

Acid neutralization • A three-component, constrained simplex-centroid mixtures design was used to select the compositions for ten solutions of vinegar and two commercial antacids. Solution pH was measured using a digital pH meter. ANOVA and linear least squares to determine a statistically significant polynomial fit of the data were used, and then contours of constant pH were plotted on triangular graph paper. By changing the brand of antacids, this experiment can be changed.

Frictional losses in pipes • The Fanning friction factor was calculated for laminar and turbulent flow in PVC and copper pipes of various diameters based on pressure drop measured using an inclined manometer. Due to time considerations, a balanced incomplete blocking design was used to select the factor space combinations to be tested. Linear regression allowed the students to determine if the Hagen-Poiseuille law was valid.

Rotameter calibration • A blocking design, using the operator as the blocking factor and rotameter reading as the independent factor, was used to determine the experimental space to create a calibration curve for a salt-water solution in a rotameter. ANOVA was used to identify the significant factors and linear regression was used to develop a calibration curve and a 95% confidence interval for the predicted values. This experiment was changed by altering the density of the fluid used in the rotameter.

Efficiency of a parallel-plate exchanger • A 2^{4-1} fractional factorial was used to evaluate the efficiency of a simple parallel-plate heat exchanger (custom designed and manufactured for this course) using the inlet temperatures and flow rates as the independent factors. The students had to calculate the overall resistance to energy transfer for both the cold and hot sides, determine if they were affected by any of the factors, and decide whether or not the two coefficients were statistically different. By changing the number of plates in the exchanger and the thickness of the plates, the experiment could be altered.

Viscosity of aqueous solutions • The effect of a proprietary food thickener on the apparent viscosity of aqueous solutions as a function of shear rate and thickener concentration was measured using a rotating spindle viscometer. A two-level nested design was used to determine the factor space combinations to be tested, and ANOVA was used to analyze the data. Changing the concentration and type of thickener changed the experiment from group to group.

The second most common reaction was that the experiments were relatively simple to conduct and that they could easily be accomplished in the allotted time. Having both the in-lab preview and oral presentations by other students greatly facilitated this efficiency. But there were some problems with completing the experimental design (*i.e.,* completely specifying all the trials, including replicates, that would be done) prior to beginning the experiments. In several cases this meant that the students failed to conduct a sufficient number of experiments to conduct a satisfactory analysis of their data.

The students also appreciated the fact that the experiments were always ready to run. Thanks to the help of an outstanding teaching assistant and staff engineer, the experiments were turned on and warmed up before the students arrived in the lab; the students did not have to wait for water baths to heat or for instrumentation to warm up before they were ready to begin. The teaching assistant and staff engineer were available to answer questions during the lab and to help solve equipment problems that arose (which happened about once every other week). The students truly appreciated the willingness to help and approachability of both individuals.

Little comment was made by students regarding the use of a technical editor to assist in grading the written reports. The editor commented on the marked improvement of the writing as the semester progressed, however. Having to write six memorandum reports and three formal reports gave the students ample opportunity to improve—the average writing grade increased by nearly 5 points (out of a possible 20) over the course of the semester. The students also made little comment about the oral and poster presentations. Again, grades significantly improved during the semester—the average grade on the initial oral reports was ten points (on a 50-point scale) lower than the average grade on the final oral reports.

The most frustrating aspect of the course for many students was the different backgrounds in statistics of the students. In addition to the statistics course offered in the department, other courses were accepted as satisfying the course prerequisite. Most of the other courses did not have the same emphasis on data analysis as the departmental course and instead focused on probability and combinatorial theory. Students who had taken the departmental course often found themselves teaching the other students how to conduct the data analysis and interpret their data. Although this was probably a great learning experience for the students, they resented the time it required for what to them was no return.

TABLE 2
Summary of Experiments, Experimental Designs, and Engineering Topics Covered in the First Laboratory Course

Experimental Design	Engineering Topic: *Heat Transfer*	*Mass Transfer*	*Momentum Transfer*	*Chemical Reaction*	*Physical Properties*
Graeco-Latin Square	Heat Transfer From Fins		Efflux Time From a Baffled Tank		
Fractional Factorial	Parallel Plate Heat Exchanger	Adsorption by Activated Carbon			
Constrained Mixtures				pH of Aqueous Solutions	Specific Gravity
Blocking			Frictional Losses in Pipes		
Nested					Viscosity of Aqueous Solutions

LESSONS LEARNED AND RECOMMENDATIONS

In general, the laboratory worked extremely well considering it was the first time the course was offered in this manner. From the instructional side, the following lessons were learned (or, in some instances, relearned):

- To compliment the experiments, the initial phase of the course needed to focus more on how to develop a design so that the proper factor space combinations and replicates would be tested. In the lab manual, the experimental design was specified, but the details were left for the student to determine, which they did not always complete prior to the experiments.
- To improve the written and oral communication skills, more time needed to be devoted to reviewing the structure and organization of technical communication during the initial phase of the course. In conjunction with this, reviewing document design aspects would also be warranted.
- To assist students who had taken a non-departmental experimental statistics course, grouping them together and reviewing the design and analysis techniques weekly assisted in reducing both the intra- and inter-group variability.
- To provide sufficient time for data analysis, the laboratories should be conducted on Thursdays, with the reports due on the following Tuesday. Initially, the labs were done on Tuesdays, with reports due Thursday—leaving insufficient time to conduct the analysis.
- To enhance the quality of the formal reports, students need to cover a broader scope of material than the experiments for the memorandum reports. For example, the mixtures experiments could involve a fourth component or the evaluation of the heat exchanger could include the effects of the

number of plates.

- To ensure that the students can complete the experiments in time, a hands-on teaching assistant is absolutely necessary.
- To reduce student frustration at having to work for an extended period of time with an under-achieving lab partner, groups need to be reformed randomly and frequently. Having each student work in three groups over the semester seemed to avoid intra-group problems.

In addition to addressing the lessons above, the following recommendations are also suggested:

- To cover more chemical engineering science (in particular, chemical reactions and kinetics), a greater breadth of experiments is needed.
- To further improve the writing skills, it would have helped if report writing would have included revising some of the reports until all structure, organization, and grammatical problems were corrected.

ACKNOWLEDGMENTS

Without the energy and expertise of Jim Anthony and James Autry, this laboratory would not have been as successful as it was. Jim Anthony, the departmental engineer, was responsible for building and assembling the experiments. James Autry, my teaching assistant, was responsible for making sure that the experiments were operating every week and answering questions about experimental procedures and laboratory safety. I am also thankful for the comments made by one of the reviewers about the value of exploring topics not yet covered in courses.

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Vapor-Liquid Equilibria

Continued from page 79.

defined by $K_i=y_i/x_i$. Of special interest is a plot of contours for $K_i=1$, as shown in Figure 8. Since points at which $K_i=1$ indicate that the mole fraction of a particular component is identical in both phases, any point at which the three individual $K_i=1$ contours intersect defines a ternary azeotrope. Thus, Figure 8 contains a ternary azeotrope at a composition of 7% acetone, 62% methyl acetate, and 31% methanol, in good agreement with Figure 7 and indicating self-consistency in the students' calculations. Certainly, the ternary plot should also predict any binary azeotropes. For example, the intersection of $K_i=1$ contours for acetone and methanol, along the edge in which the methyl acetate mole fraction is zero, reveals an acetone-methanol binary azeotrope at a methanol mole fraction of 0.2. This result is in excellent agreement with that of Figures 5 and 6.

OTHER CONSIDERATIONS

A technical detail to consider when planning the experiment outlined in this paper is the requirement for constant pressure. Whereas the data reduction (specifically, Eq. 4) assumes constant pressure, the actual system pressure is subject to atmospheric changes. Occasionally, students may face the challenge of performing the experiment as a storm front approaches and the atmospheric pressure changes appreciably. It is therefore imperative that students be able to handle pressure fluctuations, either during data reduction by modification of Eq. (4) to include a pressure dependence or (preferably) by correcting the measured boiling points for changes in pressure during the lab session. Even if the correction turns out to be negligible, good engineering practice requires that this be tested rather than assumed. We therefore view systematic pressure variation as a fortunate event because it affords students the opportunity to think through the aberration and account for the effect.

Finally, a remaining consideration that may be of critical concern is one of cost. Price quotes for the main components in our system are \$800 (Swietoslawski ebulliometer), \$1900 (hot water circulator), \$650 (digital temperature display), \$120 (pump), \$125 (HDPE tank), and \$130 (platinum RTD).[13] The capital cost for a simple VLE experiment involving a single ebulliometer is therefore approximately \$3700 (plus associated piping), although time limitations would likely limit such an experiment to a single binary system. Reproducing the ternary VLE experiment we have described requires a capital expenditure on the order of \$15,000.

CONCLUSIONS

Our undergraduate VLE experiment has evolved over several decades and has been in its current form the past five years. We believe that it is unique because it allows generation of ternary phase behavior from a single afternoon of data collection.[14] The lab is therefore educational in two very important general aspects. One is the technical training that the lab provides, since students demonstrate a greatly improved understanding of phase behavior and sharpen their modeling skills as a direct result of the laboratory work. Another is the practical lesson students learn; that time and money are important considerations when planning any experiment, and reasonably accurate data can often be obtained without elaborate measurement techniques.

We invite you to visit our VLE website at
http://www.che.udel.edu/cheg345

ACKNOWLEDGMENT

The authors wish to thank Professor Jon Olson and Dr. Larry Dodd for contributions in the early stages of development of this experiment.

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9. Strictly speaking, Eq. (5) is a truncated version of the ternary van Laar model. Eq. (5) neglects all terms of third and higher order in the volume fractions that appear in the Wohl expansion for the excess Gibbs free energy.
10. Gmehling, J., and U. Onkne, "Vapor Liquid Equilibrium Data Collection" Chemistry Data Series, Vol. 1, Part 1, DECHEMA, Frankfurt/Main (1977)
11. Ethanol is an adequate substitute if safety considerations preclude the use of methanol.
12. Tester, J.W., and M. Modell, *Thermodynamics and Its Applications,* 3rd ed., Prentice-Hall, Inc., Upper Saddle River, NJ (1997)
13. Prices quoted in Spring, 1999
14. The lab operates on a four-week cycle. During week 1 students view the equipment and complete a pre-laboratory homework assignment. The experiment is performed by five teams (each with three students) during week 2, where each team is given one afternoon session (typically 3-4 hours) to obtain data. Students prepare a preliminary technical report during the third week that addresses only the binary VLE data and modeling. The ternary system is handled during week 4, in which students prepare a final technical report that addresses the feasibility of separating the three chemicals. ❐

THE ANNUAL CHE SYMPOSIUM AT CARNEGIE MELLON

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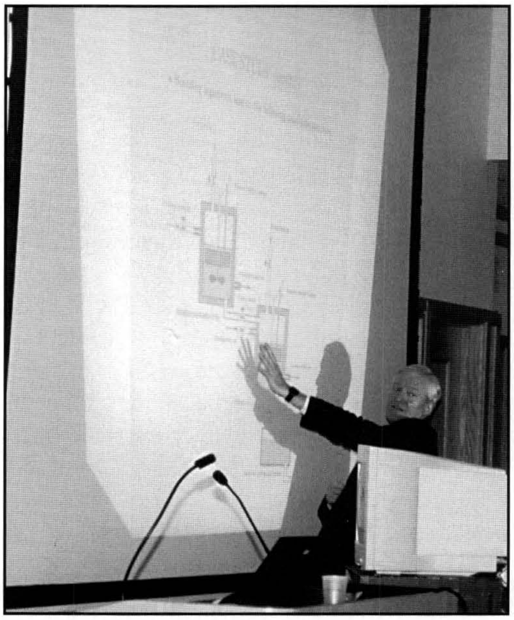


Keynote speaker, Professor John Perkins, describes a flowsheet during his talk.

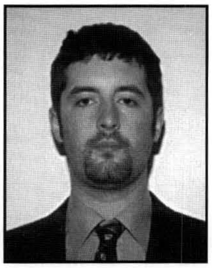
Over the past few years, chemical engineering departments in several universities around the country have begun to hold annual graduate students research symposia. This tradition began in 1979 at Carnegie Mellon when the Chemical Engineering Graduate Students Association (ChEGSA) organized the first Annual Chemical Engineering Symposium. Since that time, each symposium at Carnegie Mellon has been organized by graduate students for their colleagues and each has been funded entirely from industrial sponsorship, with all funds being raised by the students themselves. Carnegie Mellon's Twentieth Annual Symposium was held in October of 1998, and so it seems fitting to briefly review the significance of the symposium on this anniversary.

INDUSTRIAL PARTICIPATION

In 1979, Department Head Tomlinson Fort suggested holding an annual symposium, to be organized by ChEGSA. He felt the symposium would promote better communication skills among graduate students and provide a forum in which to exchange research ideas, both within the department and with industry. It has been with that objective in mind that the symposium has continued and enjoyed great success over the past twenty years.

Industrial participation commenced with the Second Annual Symposium and has become increasingly important every year since then. Because the Symposium is funded entirely through donations made by industrial participants, it allows graduate students to refresh their contacts with industry and to learn more about current industrial needs and concerns. In addition, it is a useful way for the students to learn important networking skills and to keep in contact with alumni. Furthermore, the symposium gives industrial participants an opportunity to learn more about current departmental research and provides an excellent means for them to meet graduate students and to get to know them outside the artificially constrained atmosphere of a formal recruiting process.

For many alumni and industrial participants, the symposium provides a first point of contact for those who may be their future colleagues. For this reason, a resume book is compiled and distributed to all of the industrial participants.



Timothy D. Power is a PhD student in the Department of Chemical Engineering at Carnegie Mellon University. He received his BE degree in 1997 from University College, Dublin, Ireland, and began his graduate work at Carnegie Mellon in the fall of that year. As the 1998 Vice-President of the ChEGSA, Timothy was responsible for organizing the Annual Symposium described in this paper. He is currently working with Professor David Sholl in the area of molecular simulations.

KEYNOTE ADDRESS AND STUDENT PRESENTATIONS

Each year since 1984, the symposium has included a keynote address from a researcher and lecturer of international standing. (A full list of all the keynote speakers over the years is given in Table 1.) The purpose of the keynote address is to promote better presentation skills among the students through the example set by an outstanding speaker.

In 1998, the keynote speaker was Professor John D. Perkins, Head of the Department of Chemical Engineering and Chemical Technology at Imperial College, London. His talk, "Trends in Process Systems Engineering," was received with great interest, as it touched both on the history of process systems engineering and recent trends in design and control integration.

In recent years, the symposium has been held in a conference room on campus in mid-October. Since it takes place in mid-week, classes for all graduate students are cancelled for those days. Over the two-day period of the symposium, the PhD students in the department give approximately thirty-five presentations. While a handful of second-year students usually participate, most of the presentations are made by the third-, fourth-, and fifth-year students.

The range of research topics covered in the symposium spans all primary areas of specialization at Carnegie Mellon, specifically: bioengineering, complex fluids, environmental engineering, process systems engineering, and solid-state materials. Speakers are allotted fifteen-minute time slots for their presentations.

Since maximal industrial participation tends to occur on the first day, priority for time slots on that day is given to students in the final year of their studies. A luncheon is also held on the first day of the symposium and participating students, industrial attendees, and faculty are all invited, providing further opportunities for interaction and conversation. In addition, the poster session held that evening is accompanied by a wine-and-cheese reception where there are further prospects for contact.

TABLE 1
Keynote Speakers

1984	Ed Cussler, *University of Minnesota*
1985	Dan Luss, *University of Houston*
1986	George Keller, *Union Carbide*
1987	Alexis Bell, *University of California, Berkeley*
1988	Eduardo Glandt, *University of Pennsylvania*
1989	Robert Anderson, *Monirex Systems, UOP Inc.*
1990	Michael Shuler, *Cornell University*
1991	Michael Doherty, *University of Massachusetts*
1992	John O'Connell, *University of Virginia*
1993	Elizabeth Dussan, *Schlumberger Doll*
1994	Joe Pekny, *Purdue University*
1995	Doug Lauffenberger, *Massachusetts Inst. of Tech.*
1996	Mark Barteau, *University of Delaware*
1997	Alice Gast, *Stanford University*
1998	John D. Perkins, *Imperial College, London*

TABLE 2
1998 ChE Symposium Award Winners

Geoffrey D. Parfitt Award (Overall)

- Scott A. Guelcher: Advisor, John L. Anderson
  Investigating the Mechanism of Aggregation of Colloidal Particles During Electrophoretic Deposition

Symposium Awards

- Celia N. Cruz; Advisor, Spyros N. Pandis
  The Effect of Organic Coatings on the Cloud Condensation Nuclei Activity of Inorganic Aerosol
- Stephen J. Vinay, III: Advisor, Myung S. Jhon
  A Study of Multi-Particle Dynamics in Triboelectrostatic Systems

Honorable Mentions

- Hector Yeomans: Advisor, Ignacio E. Grossmann
  A Disjunctive Programming Method for the Synthesis of Heat Integrated Distillation Sequences
- Timothy D. Power: Advisor, David S. Sholl
  Theoretical Studies of the Adsorption of Chiral Molecules onto Chiral Metal Surfaces

SYMPOSIUM AWARDS

The ChEGSA symposium provides a unique means for students to develop the skills they will need for future success. In almost any career, it is essential to be able to present one's work to others and to argue the merits of one's case. It is not easy to deliver a short presentation to an audience with diverse interests, and practice is the best way to become comfortable and confident with making presentations. To this end, a panel of academic professors and industrial attendees adjudicate each student's talk with the intention providing feedback to the students and improving their communication skills. The speaker with the highest evaluation receives the Geoffrey D. Parfitt Memorial Award. This award, established by ChEGSA, honors the memory of Dr. Parfitt, a Professor of Chemical Engineering at Carnegie Mellon who passed away unexpectedly in 1985. There are, in addition, two awards given to the second- and third-highest ranked students, as well as two honorable mentions.

Awarding the students for their performance has proven valuable—it provides a tangible incentive for students to deliver high-quality presentations. Over the years, many who have won awards at the symposium have gone on to pursue very successful careers, *i.e.,* among others, John Walz (1991 and 1992), Yale University; Christodoulos A. Floudas (1983 and 1985), Princeton University; Annette Jacobson (1987), Carnegie Mellon University; Marco Duran (1984), Exxon Corporation; James Cuthrell (1985), Shell; Paul Bowman (1986 and 1987), Arco Chemical. The awards are presented the week following the symposium at a banquet organized by ChEGSA. A list of the award winners of the 1998 symposium is given in Table 2.

The symposium is also crucially important in assisting new first-year graduate students in selecting a thesis advisor. The symposium takes place midway through the first semester and (at Carnegie Mellon) the thesis advisor is usually not selected until late in this semester. By attending talks given by students of various faculty, the symposium provides a valuable means for first-year students to learn more about the specifics of the research they can expect to do if they work with a certain professor.

VALUE OF THE SYMPOSIUM

The continued success of the symposium can be attributed to the many benefits derived from holding such an event. In the first instance, the symposium internally benefits the Chemical Engineering Department. Graduate students are given an opportunity to learn more about the work in which their peers are engaged, and the opportunities for exchanging ideas and other feedback are substantial. In addition, the department greatly benefits from the opportunity to refresh contacts with industry.

Since it is entirely the responsibility of students, actually organizing the symposium is a valuable experience in and of itself. Its organization is generally the responsibility of just one student, with assistance from fellow ChEGSA officers. There is, of course, a considerable time investment required from the individual concerned. In addition to the logistics of accepting abstracts, allotting time slots for speakers, organizing flights for the keynote speaker, etc., there is also a considerable fund-raising element involved. As a consequence, competence in several areas is needed to successfully coordinate the event, including communication and negotiation abilities, delegating skills, fund raising, and resource allocation. Time-management skills are crucial, since the event needs to be planned while the organizer continues to pursue research, attend classes, and attends to teaching-assistant duties.

Typically, about $8,500 is required just to cover the basic costs of the symposium. Apart from the obvious costs such as the luncheon and travel expenses and honorarium for the keynote speaker, there are additional expenses that include the cost of coffee and refreshments, postage, audio-visual equipment rental, etc. All of the funding to cover these costs is derived from the donations of industrial sponsors (who donate $500 or more) and contributors (who donate $100-499).

That the symposium has been a truly valuable event at Carnegie Mellon is without question. As long as it continues to serve its purpose, it requires and deserves continued strong support from all who participate, including students, faculty, and particularly industrial sponsors and contributors, whose exceptional generosity has been more than appreciated through the years.

ACKNOWLEDGMENTS

Many thanks to my fellow ChEGSA officers for their help in organizing the symposium in 1998. Also, thanks are due to Professor David Sholl, Professor Ignacio Grossmann, and Amanda Utts for their help in writing this paper.

Thanks also must go to the 1998 industrial sponsors: Air Products and Chemicals, Inc., ALCOA, Amoco Chemical Corporation, ARCO Chemical, Aspen Technology, Inc., Bayer, BOC, Dow Chemical, Dow AgroSciences, Dupont, The Goodyear Tire & Rubber Company, Lubrizol, Merck & Company, Mitsubishi Chemical America, Monsanto Company, PPG Industries, and Simulation Sciences Inc. Industrial contributors for 1998 were Coca-Cola Company, International Paper, Johnson & Johnson, McKinsey, Mobil, Schlumberger, Sony Chemical, and Westinghouse. ❐

ChE letter to the editor

To the Editor:

I have just looked through the Fall, 1999, issue of *Chemical Engineering Education*—the well-known graduate education issue. I noticed a number of advertisements in the graduate education section that have photographs of people in laboratories who do not have proper personal protective equipment. In particular, they lack proper safety glasses.

I can assure you that our industrial friends will notice this problem. It is also contrary to a number of articles that have appeared in *CEE* discussing proper safety culture in laboratories.

Several years ago I received an award from the Chemical Manufacturers' Association. The CMA requested photographs with me and my students in the laboratory. The cover letter stated that photos without proper personal protective equipment would not be accepted. I would like to suggest that CEE do the same.

Dan Crowl
Michigan Tech

Editor's Note: We agree with the comments and encourage each advertising university to take note of this breach of laboratory safety procedures when reviewing their advertisements next year.

ChE books received

Tailored Polymeric Materials for Controlled Delivery Systems, edited by Iain McCulloch and Shalaby W. Shalaby; Oxford Uiversity Press, 198 Madison Avenue, New York NY 10016; 322 pages, $15 (1998)

Oxford Dictionary of Biochemistry and Molecular Biology, Oxford Uiversity Press, 198 Madison Avenue, New York NY 10016; 739 pages, $60 (1997)

Design of Devices and Systems, 3rd edition, by William H. Middendorf and Richard H. Engelmann; Marcel Dekker, Inc. 270 Madison Ave., New York, NY 10016-0602; 584 pages, $69.75 (1998)

New Methods in Computational Quantum Mechanics, edited by I. Prigogine and Stuart A. Rice; Wiley, 605 Third Avenue, New York, NY 10158; 813 pages, $54.95 (1997)

Organotin Chemistry, by Alwyn G. Davies; Wiley, 605 Third Avenue, New York, NY 10158; 327 pages, $180 (1997)

Hydrocarbon Resins, by R. Mildenberg, M. Zander, and G. Collin; Wiley, 605 Third Avenue, New York, NY 10158; 180 pages, $140 (1997)

Solvent-Free Polymerizations and Processes: Minimization of Conventional Organic Solvents, edited by Timothy E. Long and Michael O. Hunt; Oxford University Press, 198 Madison Ave., New York, NY 10016; 292 pages, $110 (1999)

Fluid Dynamics and Transport of Droplets and Sprays, by William A. Sirignano; Cambridge University Press, 40 West 20th St., New York, NY 10011-4211; $80 (1999)

Engineering Flow and Heat Exchange,

Revised Edition
by Octave Levenspiel
Plenum Press, New York and London (1998)

Reviewed by
Gabriel I. Tardos
CCNY

This is the first revised edition of this book, first published in 1984. Professor Levenspiel should be commended for producing such an excellent text, written specifically for engineering students. The book is a pleasure to read and offers several amusing problems, all stated in the language of students, with explanations and examples they can easily understand. Very few texts in engineering can make such a claim. I have used this text exclusively since 1992 in my teaching of unit operations to chemical engineering students. The material is broad enough, however, to also be used in mechanical engineering, and perhaps in civil engineering courses as well, to teach flow and heat transfer.

Students (especially undergraduates) tend to sell used textbooks once they finish a subject and pass their final examination. I found, with great pleasure, that *Engineering Flow and Heat Exchange* was not one of those books; seniors use it in their design courses and many graduates keep the book as a reference. This is obviously due to the wealth of information in the book and the ease with which the information can be retrieved and used. Inclusion of compressible and non-Newtonian fluid flow in the fluid-mechanics section and direct-contact heat exchangers in the heat-exchangers section is a substantial achievement and significantly adds to the usefulness of the text.

One example of the book's unique approach to explaining a complex concept through humor and straightforward, easy-to-understand language is illustrated by how Professor Levenspiel explains the concept of equivalent average slurry density in the problem "Counting Canaries Italian Style." The "slurry" consists of canaries flying in the air inside a closed container. Measuring the pressure before and after the canaries are airborne, and using the Bernoulli equation, gives the change in density and therefore the number of "particles" (birds). Ingenious!

As already mentioned, the book is divided into a section on fluid mechanics and a section on heat transfer. The first part includes basic equations for isothermal flowing systems in Chapter 1, and as an example, flow of incompressible Newtonian fluids in pipes and around solid immersed objects in Chapters 2 and 8, respectively. Unlike other similar texts, the theory is kept short and the assumption is that the student has taken a prior course in fluid mechanics. It is assumed, for example, that the student is familiar with the concept of the Fanning friction factor.

Chapters 3 and 4 address compressible flow of gases (through material taken mostly from thermodynamics) and low pressure, "molecular" flows. Here the concept of "molecular slip" is introduced.

Chapter 5 contains, as mentioned above, concepts and problems of non-Newtonian flow explained in a direct and simple-to-understand fashion. The student is reminded that, in general, this complex fluid can be treated as Newtonian with an additional term and all that is required is to find the correction due to the non-Newtonian behavior. Since most fluids in industrial practice are non-Newtonian, the introduction of this material is, I think, crucial. Furthermore, rheometry to measure non-Newtonian behavior is also presented in detail.

Part one of the book also contains chapters of flow in porous media and in fluidized beds. They are also well written, with many examples and actual industrial applications both solved and presented as homework problems.

The second part of the book, on heat transfer and heat exchanger design, is also enlightening, crisp, and well constructed. Chapters 9, 10, 12, and 13 contain the usual material on different forms of heat transfer, combined heat transfer, and two-fluid heat exchanger design. Here again, it is assumed that the student has taken a previous introductory course in heat transfer since familiarity with, for example, the Nuselt number is required. The material in Chapters 11, 14, and 15 contains unsteady heating and cooling and design of direct-contact exchangers and regenerators—material usually not covered in standard texts. The second part ends (Chapter 16) with a set of recommended problems involving material contained in the book, keeping in mind practical, industrially relevant applications.

There is an extended Appendix with very useful information such as transformation of units, some material properties, dimensionless groups, and values of more important parameters such as heat transfer coefficients in different geometries. The text also comes (available to the instructor) with a set of solutions to the problems in each chapter , with every second problem being solved. The problems in the last chapter (16) all have solutions. The illustrations in the book are inspired and clear, while the nomograms, mostly for heat transfer calculations, are up-to-date and easy to use.

Over all, this is an excellent book, written with the heart. The reader can visibly appreciate this. It should be a permanent fixture on the bookshelf of any engineer who studied or uses fluid flow and heat transfer in his work. ❐

A MAXWELL-STEFAN EXPERIMENT

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Fickian mass transport is deeply rooted in the culture of many engineering institutions, universities, and companies. The mathematical equation that describes Fick's law is simple and intuitive, but it is only valid for binary mixtures or for diffusion of diluted species in a multicomponent mixture, in the absence of electrostatic or centrifugal force fields.[1]

The Maxwell-Stefan equation provides a better and a more general approach. To show its relevance, while keeping the mathematical treatment simple, we propose a ternary mass diffusion transport experiment and its simulation. The simulator was developed to solve the Maxwell-Stefan equation for multicomponent isobaric and isothermal systems and is readily available on the web (http://raff.fe.up.pt/~lepae/simulator.html).

The concepts presented in this work are particularly suited for both undergraduate and graduate chemical engineering students provided that they are familiar with the first and second Fick laws.

THEORETICAL BACKGROUND

The Maxwell-Stefan equation for an isothermal and isobaric multicomponent system, where only pressure forces act, is (a simple derivation of this equation is presented in the appendix)[1-3]

$$-\frac{x_i}{\Re T}\frac{d\mu_i}{dz}=\sum_{\substack{j=1\\j\neq i}}^{n}\frac{x_jN_i-x_iN_j}{c_t\mathfrak{D}_{ij}} \tag{1}$$

where x_i is the i-solute molar fraction, T is the absolute temperature, $\Re$ is the ideal gas constant, μ_i is the molar chemical potential, z is the axial coordinate, c_t is the total molar concentration, N_i is the molar flux of the species i with respect to a fixed referential, and $\mathfrak{D}_{ij}$ is the Maxwell-Stefan i,j diffusivity, with $\mathfrak{D}_{ij}=\mathfrak{D}_{ji}$.[2]

For ideal gases, Eq. (1) becomes

$$\frac{1}{\Re T}\frac{dx_i}{dz}=-\sum_{\substack{j=1\\j\neq i}}^{n}\frac{x_jN_i-x_iN_j}{P_t\mathfrak{D}_{ij}}=-\sum_{\substack{j=1\\j\neq i}}^{n}\frac{x_jJ_i-x_iJ_j}{P_t\mathfrak{D}_{ij}} \tag{2}$$

where P_t is the total pressure and J_i is the molar flux of the species i with respect to the mixture molar average velocity

$$J_i=N_i-x_i\sum_{k=1}^{n}N_k$$

For ternary systems, the Maxwell-Stefan equations are

$$\frac{dx_A}{dz}=\frac{x_AJ_B-x_BJ_A}{c_t\mathfrak{D}_{AB}}+\frac{x_AJ_C-x_CJ_A}{c_t\mathfrak{D}_{AC}} \tag{3}$$

$$\frac{dx_B}{dz}=\frac{x_BJ_A-x_AJ_B}{c_t\mathfrak{D}_{AB}}+\frac{x_BJ_C-x_CJ_B}{c_T\mathfrak{D}_{BC}} \tag{4}$$

and

$$\frac{dx_A}{dz}+\frac{dx_B}{dz}+\frac{dx_c}{dz}=0 \tag{5}$$

Equation (2) is nonlinear and therefore when solving diffusion problems it is more practical to revert it to the Fickian form

$$(J)=-c_t[D]\frac{\partial(x)}{\partial z} \tag{6}$$

where (J) and (x) are (n-1)-component column vectors of diffusion fluxes and molar fractions, respectively, and [D] is the (n-1)x(n-1) Maxwell-Stefan diffusion coefficient matrix

$$[D]=[B]^{-1} \tag{7}$$

and [B] is the diffusion coefficient inverse matrix that is obtained from Eq. (2)

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***Paulo Cruz** is a first-year Ph.D. student in Chemical Engineering at the University of Porto, Portugal, where he received his degree in Chemical Engineering in 1998. His research interests are multicomponent mass transport and sorption in porous solids and membranes.*
***Adélio Mendes** received his degree and Ph.D. in Chemical Engineering from the University of Porto, Portugal, where he is currently Assistant Professor. He teaches Chemical Engineering Laboratories, Separation Processes, and Numerical Methods. His main research interests include membrane and sorption gas separations.*

$$B_{ij} = \frac{x_i}{\mathfrak{D}_{in}} + \sum_{\substack{k=1 \\ k \neq i}}^{n} \frac{x_k}{\mathfrak{D}_{ik}}, \quad B_{ij(i \neq j)} = -x_i \left(\frac{1}{\mathfrak{D}_{ij}} - \frac{1}{\mathfrak{D}_{in}} \right), \quad i,j = 1,2,3, \cdots n-1 \quad (8)$$

The Maxwell-Stefan diffusivities can be estimated by the Chapman-Enskog Eq. (9)[4]

$$\mathfrak{D}_{ij} = 5.9543 \times 10^{-24} \frac{\sqrt{T^3 \left(\frac{1}{M_i} + \frac{1}{M_j} \right)}}{P_T \sigma_{ij}^2 \Omega_{D,ij}} \quad (9)$$

where σ_{ij} is collision diameter, $\Omega_{D,ij}$ is the collision integral, and M_i is the molecular mass of species i (all the units are in SI). The collision parameters can be found, for instance in Bird, et al.[4]

EXPERIMENTAL SETUP

The experiment described below shows the limitations of Fick's equation and introduces the Maxwell-Stefan equation for multicomponent diffusion. The setup is shown in Figure 1.

Typically, two tanks of about the same volume are connected by a 4.3-mm internal diameter pipe (1/4" nominal diameter) that is 15.3 cm long. Tank A has a 45.2-cm^3 volume, while tank B has a 41.5-cm^3 volume. An on/off valve divides the pipe at the middle and has about the same pipe internal diameter. A set of needle valves, on/off valves, and a pressure transducer are available to fill up the tanks. All the valves are made of stainless steel by Whitey. The pressure transducer (Druck model PDCR921) has an 0-70 kPa absolute pressure range with ±0.5% F.R.S. precision. Gas analysis is made at a high frequency by a mass spectrometer (Dataquad, from Spectramass, UK) connected to one tank at a time. The mass spectrometer sample probe is made of a 1-m long fused silica column with 50 μm internal diameter. After two hours the total pressure changes less than 1% due to this mass withdraw when the initial pressure is 40 kPa (absolute pressure). A vacuum pump evacuates the system to a pressure below 0.3 kPa. All data are recorded on a computer every 100 seconds.

Students evacuate both tanks and then fill them with equimolar binary gas mixtures with the help of the pressure transducer. They should fill both tanks with nitrogen at the same time, up to a pressure of 20 kPa (absolute pressure), and then add helium to tank A and carbon dioxide to tank B, up to a total pressure of 40 kPa. At the end, both tanks must have the same total pressure. When changing the feed gas, the filling circuit should be evacuated—otherwise the residual gas will enter with the new feed gas. Nitrogen is the common component in both tanks.

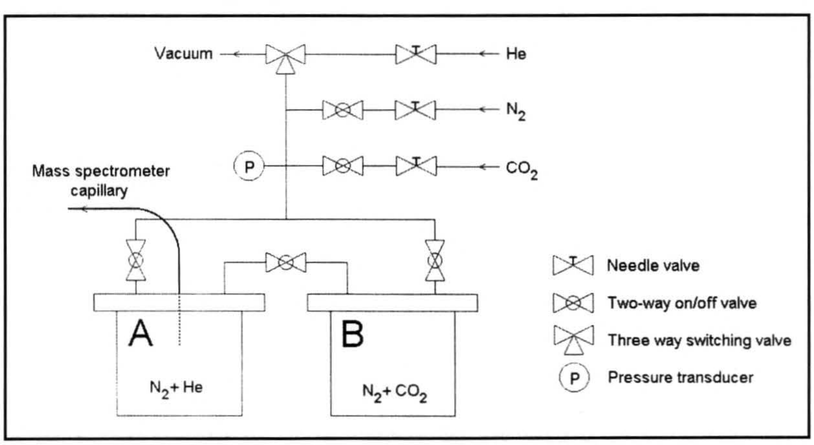

Figure 1. *Sketch of the experimental setup.*

After filling the tanks, students are asked to start the data acquisition software, to switch on the mass spectrometer, to read the temperature, and to open the switching valve connecting the tanks. Helium diffuses from tank A to tank B, and carbon dioxide diffuses from tank B to tank A. The total pressure difference between the tanks should be negligibly small, implying no viscous flow and so equimolar diffusion.

The diffusion constant is approximately inversely proportional to the total pressure. A total pressure of 40 kPa allows students to complete the diffusion experiment within the three-hour laboratory session.

The experiment should be performed twice, switching the tanks' contents on the second run in order to record the concentration history of both tanks. This can be done in two consecutive classes of three hours each by two different student groups. The two groups, working as a team, should exchange their results and draw the nitrogen molar fraction curves as a function of time. Then they can simulate their experimental system with the available simulator and comment on the results.

DATA TREATMENT AND DISCUSSION OF RESULTS

After opening the connecting valve, the gas mixtures in the tanks enter in contact (see Figure 1). The connecting pipe mass balance can be written as[4]

$$\frac{\partial N_i}{\partial z} + \frac{\partial c_i}{\partial t} = 0 \quad (10)$$

Since the total pressure gradient between the tanks can be neglected, there is no viscous flow, and therefore the total flux, N_t, is zero. Introducing Eqs. (6) and (7) into the mass balance, the following expression is obtained for constant temperature and pressure:

$$\frac{\partial(N)}{\partial z}+\frac{\partial(c)}{\partial t}=\frac{\partial}{\partial z}\left[-c_t[D]\frac{\partial(x)}{\partial z}\right]+c_t\frac{\partial(x)}{\partial z}=$$

$$c_t[B]^{-1}\frac{\partial[B]}{\partial z}[B]^{-1}\frac{\partial(x)}{\partial z}-c_T[B]^{-1}\frac{\partial^2(x)}{\partial z^2}+c_t\frac{\partial(x)}{\partial z} \qquad (11)$$

where the matrix product is not commutative. In the case of three-component diffusion, a two-component matrix equation (Eq. 11) must be considered along with the total flux: N_t=0. Assuming that the diffusion time constant inside the tanks is much smaller than the diffusion time constant in the pipe, the tanks can be considered as completely stirred. The mass balance of the complete system (Figure 1) is

$$V_A\frac{\partial c_i\big|_{z=0}}{\partial t}-A\,N_i\big|_{z=0}=0 \qquad (12)$$

for tank A, and

$$V_A\frac{\partial c_i\big|_{z=0}}{\partial t}-A\,N_i\big|_{z=0}=0 \qquad (12)$$

for tank B. L is the pipe length.

A fortran program, using an MS Excel interface, was written to solve this problem. The program is also available on the web <http://raff.fe.up.pt/~lepae/simulator.html> for remote simulation. It can be applied to mixtures of 3 to 7 components. For solving the partial differential equations, along with the ordinary differential equations, the package FORSIM VI[5] was used.

At the beginning the nitrogen concentration is the same in both tanks and therefore, according to the Fick equation, nothing should happen to it. Figure 2 shows the concentration curves for the three gases in both tanks. As can be seen, the concentration of nitrogen starts to decrease in tank B and to increase in tank A! Why? Helium and carbon dioxide seem to behave as Fickian gases: helium concentration decreases in tank A and carbon dioxide in tank B until equilibrium is reached. The step-like behavior of some experimental points in Figure is related to the mass spectrometer resolution.

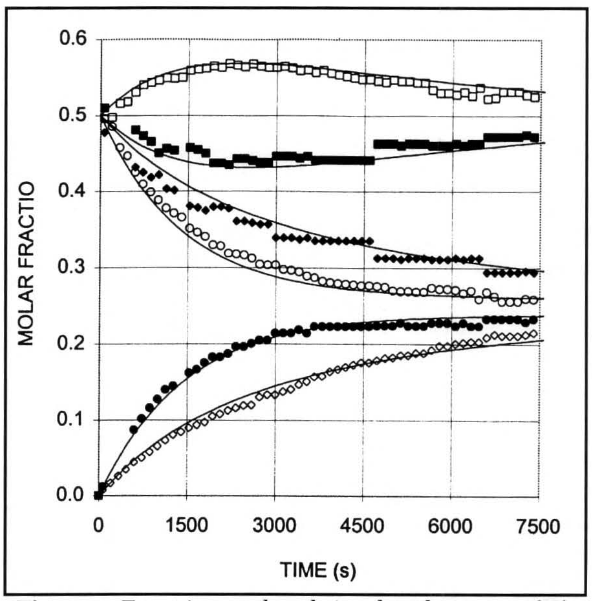

***Figure 2.** Experimental and simulated nitrogen (■), helium (●), and carbon dioxide (◆) molar fraction curves as a function of time. Open symbols refer to tank A and closed symbols to tank B. The solid lines represent the simulated results.*

The diffusion coefficients of the three gas pairs at 40 kPa and 20°C are

$$\mathfrak{D}_{He-N_2}=\mathfrak{D}_{N_2-He}=1.7076\times10^{-4}\ m^2/s$$

$$\mathfrak{D}_{He-CO_2}=\mathfrak{D}_{CO_2-He}=1.4172\times10^{-4}\ m^2/s$$

$$\mathfrak{D}_{N_2-CO_2}=\mathfrak{D}_{CO_2-N_2}=0.3688\times10^{-4}\ m^2/s$$

Helium binary coefficients are high and it readily moves from tank A to tank B while carbon dioxide moves slowly from tank B to tank A. Nitrogen should balance these effects, and so it first moves with carbon dioxide from tank B to tank A, to balance the very fast helium, and then returns to tank A. Students are asked to internalize this picture in opposition to the one given by Fick's law, where mass transport is viewed as depending only on each component concentration gradient.

The mass spectrometer allows for an almost continuous concentration measurement. If not available, a different experiment can be performed using a gas chromatograph. Two samples can be collected from each tank using a syringe. In this case, the tanks' total pressure should be 1 atm or more, to allow sampling. The samples can be collected at the highest and lowest nitrogen partial pressures, and the time at which this happens can be estimated from the simulation program.

CONCLUSIONS

Fick's equation is "intuitive" and deeply rooted in the culture of many engineering institutions. While very simple, it is only valid for binary systems or multicomponent diluted systems. To change the Fickian culture and internalize a new feeling in the diffusion area, we propose to the students a ternary diffusion lab exercise. The gases considered (helium, carbon dioxide, and nitrogen) are neither dangerous nor expensive. The experimental setup is also inexpensive, provided that a mass spectrometer is available.

The experiment is very simple and can be easily performed in 3 hours. It also strongly demonstrates the inaccurate results that Fick's equation can lead to under some circumstances. The simulation program that supports this experiment allows students to play at home with different systems, helping them to gain a new feeling for multicomponent diffusion mass transport.

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NOMENCLATURE

A connecting pipe cross-section area (m^2)

c_i molar concentration of species i (mol m^{-3})
c_t total molar concentration (mol m^{-3})
D_{AB} Fickian A,B diffusivity (m^2s^{-1})
D_{AM} Fickian diffusivity of species A in a mixture (m^2s^{-1})
$\mathfrak{D}_{AB}$ Maxwell-Stefan A,B diffusivity (m^2s^{-1})
F molar force (N mol^{-1})
J_i molar flux of species i with respect to the mixture molar average velocity (mol $m^{-2}s^{-1}$)
(J) (n-1)-component column vector of diffusion fluxes (mol $m^{-2}s^{-1}$)
L connecting pipe length (m)
M_i molecular mass of species i (kg mol^{-1})
N_i molar flux of species i with respect to a fixed referential (mol $m^{-2}s^{-1}$)
N_t total molar flux with respect to a fixed referential (mol $m^{-2}s^{-1}$)
p_i partial pressure of species i (Pa)
P_t total pressure (Pa)
$\Re$ ideal gas constant (J $mol^{-1}K^{-1}$)
t time (s)
T absolute temperature (K)
V_A,V_B volume of tanks A and B, respectively (m^3)
u_i velocity of species i (ms^{-1})
x_i molar fraction of species i (dimensionless)
(x) (n-1)-component molar fractions vector
z axial coordinate (m)

Greek Letters

μ_i molar chemical potential (J mol^{-1})
σ_{ij} collision diameter (m)
$\Omega_{D,ij}$ collision integral (dimensionless)

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APPENDIX

Derivation of the Maxwell-Stefan Equation (Based on References 1, 2, and 3)

Consider a pipe filled with an isobaric binary gas mixture, components A and B. When moving, component A exerts a force on B. This drag force should be proportional to the molar concentrations of B and A and to the relative velocity of both components

$$F \propto c_A c_B (u_A - u_B) \tag{A1}$$

where c_i is the i-component molar concentration, u_i is the i-solute velocity referred to a fixed referential, and F is the drag force. On the other hand, when considering an infinitesimal pipe slice, the pressure exerted by component A on the imaginary left boundary is $p_{A|z=z}$ and on the right boundary is $p_{A|z=z+dz}$, where p_A is the partial pressure of A. The partial pressure gradient $-dp_A/dz$ is the driving force for component A to move inside the pipe and should be balanced by the drag force

$$-\frac{dp_A}{dz} \propto c_A c_B (u_A - u_B) \tag{A2}$$

Calling $\mathfrak{D}_{AB}/\Re T$ to the proportional factor, we obtain

$$-\frac{dp_A}{dz} = \frac{c_A c_B (u_A - u_B)}{\mathfrak{D}_{AB}/\Re T} \tag{A3}$$

For ideal gas mixtures, Eq. A3 simplifies to

$$-\frac{dx_A}{dz} = \frac{x_A x_B (u_A - u_B)}{\mathfrak{D}_{AB}} \tag{A4}$$

For ternary mixtures, we must add an additional drag force term to the right-hand side of Eq. A4 to account for A-C interactions

$$-\frac{dx_A}{dz} = \frac{x_A x_B (u_A - u_B)}{\mathfrak{D}_{AB}} + \frac{x_A x_C (u_A - u_C)}{\mathfrak{D}_{AC}} \tag{A5}$$

and for multicomponent systems

$$-\frac{dx_i}{dz} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{x_i x_j (u_i - u_j)}{\mathfrak{D}_{ij}} \tag{A6}$$

The Maxwell-Stefan equation is usually written in terms of molar fluxes: $N_i=c_iu_i$. Replacing the velocities in Eq. A6 by molar fluxes, we obtain

$$-\frac{dx_i}{dz} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{x_i N_j - x_j N_i}{c_t \mathfrak{D}_{ij}} \tag{A7}$$

The driving force is better represented by the chemical potential gradient

$$-\frac{dx_i}{dz} = -\frac{x_i}{\Re T}\frac{d(\Re T \ell n\, x_i)}{dz} \approx -\frac{x_i}{\Re T}\frac{d\mu_i}{dz} \tag{A8}$$

and introducing this result into Eq. A7, we obtain

$$-\frac{x_i}{\Re T}\frac{d\mu_i}{dz} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{x_i N_j - x_j N_i}{c_t \mathfrak{D}_{ij}} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{x_i J_j - x_j J_i}{c_t \mathfrak{D}_{ij}} \tag{A9}$$

This is the usual form of the Maxwell-Stefan equation for isobaric and isothermal systems, where only pressure forces are present.

For binary mixtures, the Maxwell-Stefan equation reduces to the Fick equation

$$J_A = -c_t D_{AB} \frac{dx_A}{dz} \tag{A10}$$

and the Maxwell-Stefan diffusivity is the same as the Fickian binary diffusivity. For multicomponent systems, the Fick equation is written as

$$J_A = -c_t D_{AM} \frac{dx_A}{dz} \tag{A11}$$

where D_{AM} is the diffusion coefficient of A in the multicomponent mixture. While the Maxwell-Stefan diffusion coefficients can be considered essentially constant with the composition, the Fickian diffusivity cannot, even for ideal gases and equimolar diffusion.[4] ❐

A DIMENSIONAL EQUATION FROM ENVIRONMENTAL ENGINEERING

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Generally, we prefer to work with equations that are formulated to be independent of any particular system of units. This is not always convenient to do, and we use many equations that are valid only for a particular system of units. The undergraduate encounters these throughout the chemical engineering curriculum. The appearance of "g_c" in many equations in texts of American origin prompts the reader to the fact that the units are English of the American variety. Students meet examples of dimensional equations into which values of variables must be entered with particular units; examples of these are empirical correlations for heat and mass transfer coefficients given in the text of McCabe, et al.[1]

The need to find empirical correlations has probably been the prime source of dimensional equations. In environmental engineering and science, many empirical correlations involve a relationship between the quantity of interest and the octanol-water partition coefficient, K_{ow}. This coefficient was originally used by medicinal chemists[2,3] interested in finding correlations for equilibrium and transport properties of chemicals within living systems. Many useful correlations involving the octanol-water partition coefficient[4,5] exist; these include measures of toxicity, measures of accumulation of chemicals by organisms as well as molecular properties such as water solubility, Henry's law constants, molar volumes, and measures of a chemical's surface area.

We wish to discuss the correlation that is widely used for doing an order-of-magnitude estimation of the distribution of hydrophobic chemicals in aquatic systems. It is

$$K_{oc} \cong \alpha \times K_{ow} \tag{1}$$

Here, K_{oc} is the sediment, or soil, sorption coefficient and α is a constant, whose values are typically 1.0[6] and 0.6.[7] A more general form that is often used is

$$\log K_{oc} = a \cdot \log K_{ow} + b \tag{2}$$

The definitions of the coefficients are

$$K_{oc} = \frac{C_s}{F_{oc} C_{aq}} \tag{3}$$

$$K_{ow} = \frac{C_{oct}}{C_{aq}} \tag{4}$$

Here, C_s is the mass of chemical per unit mass of dry sediment or soil, F_{oc} is the fraction of organic carbon in the dry sediment or soil, C_{aq} is the mass of chemical per unit volume of aqueous phase, and C_{oct} is the mass of chemical per unit volume of octanol. The common use of the organic-carbon normalized distribution coefficient, K_{oc}, for nonionic organic chemicals arose out of the work of Karickhoff and coworkers;[7] they measured distribution coefficients, using substrates containing various fractions of organic carbon, and demonstrated that the normalized form is essentially independent of the substrate type. Similar observations, involving an organic matter basis (to be discussed later), had been made earlier.[8-10] Recent texts[5,11] contain more de-

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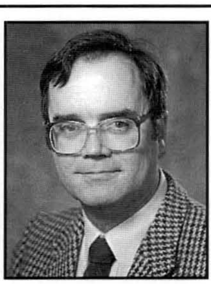

tailed descriptions.

Equations (1) and (2) are usually used in a tacitly dimensional way with the chosen units being SI units; generally, values of α are given without units, K_{ow} is unitless, and K_{oc} has units of L/kg or mL/g. Our purpose here is to ask, "What is a dimensionally consistent form of these equations?" We wish to show there is pedagogical value in answering this. In our view, the dimensional inconsistency arises from the fact that the concentration bases are different. The concentration of the chemical in sediment or soil, C_s, is defined as the mass of chemical per *unit mass of dry sediment or soil* and the concentration of the chemical in octanol is defined as the mass chemical per *unit volume of octanol.* So, to obtain a dimensionally consistent equation we should ensure that we have the same composition basis. To do this, we imagine octanol as a sample of soil or sediment.

By definition

$$C_{oct} = \frac{m}{V_{oct}} \tag{5}$$

where m is the mass of chemical in the volume of octanol V_{oct}. Using the density of octanol, ρ_{oct}, and the mass of octanol, M_{oct}, we transform this equation to

$$C_{oct} = \frac{m}{M_{oct}}\rho_{oct} = C_s\rho_{oct} \tag{6}$$

We recognize the term m/M_{oct}, the mass of chemical per unit mass of octanol, is equivalent to C_s. Keeping in mind the form of Eq. (3), we write

$$C_{oct} = C_s\rho_{oct} = \left(\frac{C_s}{F_{oc}}\right)\left(F_{oc}\rho_{oct}\right) \tag{7}$$

where F_{oct} is the *fraction of organic carbon in octanol.* Dividing through by the aqueous concentration of the chemical, we obtain the equation

$$K_{oc} = \frac{K_{ow}}{F_{oc}\rho_{oct}} \tag{8}$$

and this is dimensionally consistent. Recognizing that all the carbon in octanol is organic, we calculate the fraction of organic carbon in octanol from the relative atomic and molecular masses; F_{oc} = 0.738. The density of octanol[12] at 20°C is 0.827 g/mL. So, at 20°C,

$$K_{oc} = 1.638 K_{ow} = K_{oc}^{oct} \quad \text{or} \quad \log K_{oc}^{oct} = \log K_{ow} + 0.214 \tag{9}$$

This transformation gives the octanol-water partition coefficient on the same composition basis as the sediment, or soil, sorption coefficient. It is still the octanol-water partition coefficient, but expressed on a different basis. To emphasize this, we now designate it as K_{oc}^{oct}. This is a very unusual way of expressing compositions; the transformations between concentrations, in terms of molarity or molality, and mole fractions are much more familiar to us.

So, given a value of the octanol-water partition coefficient on its normal basis, we can calculate it on an organic carbon basis. The question now is, "To what extent does the octanol-water partition coefficient on the organic carbon basis correspond to the measured sediment, or soil, sorption coefficient?" If the organic carbon in the sediment behaves identically to octanol, then we expect the relationship in Eq. (9) to hold. What is observed? From experimental data, many workers have developed dimensional relationships with the general form of Eq. (2), in which values of a and b are determined by linear regression. To make the essential point here, we consider only the relationship developed in a recent comprehensive review[13] in which Baker and coworkers developed selection criteria and critically reviewed the available measurements. For $1.7 < \log K_{ow} < 7.0$, using data for 72 chemicals, they found

$$a = 0.903 \pm 0.034 \qquad b = 0.094 \pm 0.142 \qquad r^2 = 0.91$$

We wish to compare Eq. (9) with this result.

The dimensionally consistent relationship that we derived, Eq. (9), however, requires a=1. Using the data in the review,[13] we applied a regression model[14] in which we forced a to be unity. We obtain

$$\log K_{oc} = \log K_{ow} - (0.29 \pm 0.05) \qquad r^2 = 0.90 \tag{10}$$

In Figure 1, we have plotted the data, the regression line (Eq.

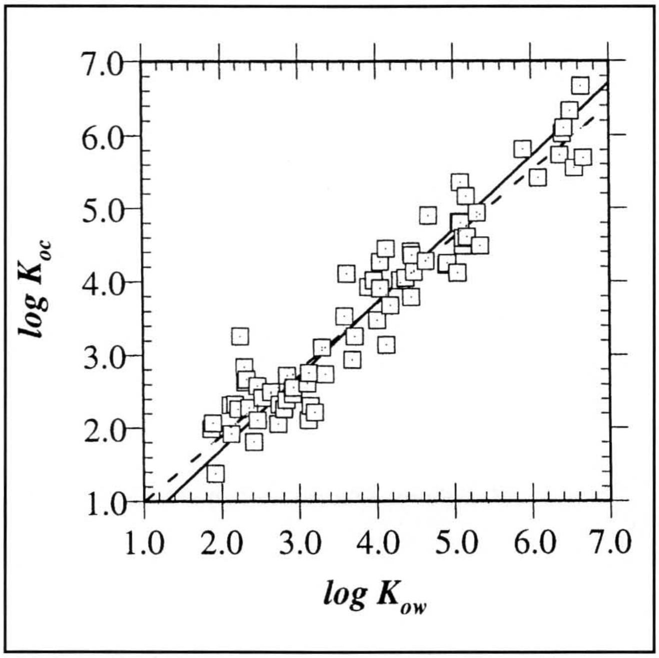

Figure 1. *The units of K_{oc} are L/kg. Data were taken from Ref. 13. The dashed line corresponds to the regression line, Eq. (2), with a=0.903 and b=0.094. The continuous line corresponds to Eq. (10) in the text.*

2 with the values of a and b given above), and the line corresponding to Eq. (10). From Eqs. (9) and (11), we find that

$$\frac{K_{oc}(\text{observed, Eq. 10})}{K_{oc}^{oct}(\text{octanol-like behavior, Eq. 9})} = 0.31 \qquad (11)$$

In other words, experimental values of K_{oc} are about one-third of the values expected if the sediment or soil organic carbon were to have the same partitioning properties as octanol.

The conclusion hinges on an appreciation of how to express compositions in various ways; the way here for soil or sediments is peculiar to environmental work and is a useful exercise for students to work out for themselves. Another closely related example is the earlier use[8-10] of the soil sorption coefficient on an organic *matter* basis. This is defined as

$$K_{om} = \frac{C_s}{F_{om} C_{aq}} \qquad (12)$$

Here, F_{om} is the fraction of organic matter. We may derive an expression for the octanol-water partition coefficient on an organic-matter basis, K_{om}^{oct}, following the same steps as before. The result is

$$K_{om}^{oct} = \frac{K_{ow}}{F_{om} \rho_{oct}} \qquad (13)$$

Octanol is all organic "matter," so $F_{om} = 1$, and we obtain

$$K_{om}^{oct} = 1.209 K_{ow} \quad \text{or} \quad \log K_{om}^{oct} = \log K_{ow} + 0.082 \qquad (14)$$

This may be compared to the approximate experimental relationship found between the soil sorption coefficient on an organic-matter basis and the octanol water partition coefficient,[4] $K_{om} = 0.4\ K_{ow}$. Here again, we may conclude that the experimental values of K_{om} are about one-third of the values expected if the sediment or soil organic matter were to have the same partitioning properties as octanol. In contrast to octanol, the fraction of organic matter in soils is about twice the fraction of organic carbon.[5,10,11] The measurement of the fraction of organic carbon is now easier, and so the use of the organic-carbon basis is now more prevalent.

We think it is important for the student to recognize when an equation is dimensional, and it is often not immediately obvious. The answer to the question, "Why is the sediment, or soil, partition coefficient less than the octanol-water partition coefficient?" is a useful entry point into a discussion of the structure of sediment, or soil, particles (a heterogeneous solid system) and the nature of adsorption. This is in contrast to distribution of a chemical between two essential homogeneous liquid phases, as represented by the octanol-water partition coefficient.

Problems

1. The composition of a phase is usually described by the mole fractions of the various components. Why is it impractical to describe the composition of a soil or sediment in terms of mole fractions?
2. Equation (10) is a dimensional equation in which the units are SI. What is the equivalent equation in English units?
3. Ten milligrams of naphthalene is added to a container that contains 10 g of sediment (dry wt), 50 mL of water, and 5 mL of octanol. The system is allowed to reach equilibrium. What are masses of naphthalene in the sediment, water, and octanol at equilibrium? The sediment contains 5% organic carbon and the octanol-water partition coefficient for naphthalene is about 2000.

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